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STUDY OF THE APPLICATION OF ADVANCED TECHNOLOGIES TO LONG-RANGE TRANSPORT AIRCRAFT

VOLUME II

RESEARCH AND DEVELOPMENT REQUIREMENTS

By R. H. Lange
R. F. Sturgeon
W. E. Adams
E. S. Bradley
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J. P. Hancock
J. W. Moore

Prepared under Contract No. NAS1-10701 by

LOCKHEED-GEORGIA COMPANY
A Division of the Lockheed Aircraft Corporation
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For
NATIONAL AERONAUTICS
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FOREWORD

Contract NAS1-10701 between the National Aeronautics and Space Administration and the Lockheed-Georgia Company, effective April 16, 1971, provided for the study of the application of advanced technologies to long-range transport aircraft. The contract was sponsored by the Office of Advanced Research and Technology and managed by Mr. W. J. Alford, Head of the Advanced Transport Technology Program Office at the Langley Research Center.

At the Lockheed-Georgia Company, the study was performed under the cognizance of Mr. J. B. Hippler, the Advanced Transport Technology Program Manager, and Mr. R. H. Lange, the Advanced Transport Technology Study Manager.

Measurement values contained in this report are in both customary and SI units with the former stated first and the latter in parentheses. The principal measurements and calculations have been made in the customary system of units.

This document, which comprises two volumes, is the final technical report summarizing the studies performed and is submitted in fulfillment of the terms of the above contract.

CONTENTS

SYMBOLS

C_L	lift coefficient
J	torsional constant
M	Mach number
R_N	Reynold's number
S	wing area, feet^2 (meters^2)
V_{MO}	maximum operating velocity, feet/second (meters/second)
W	weight, pounds (kilograms)
g	acceleration of gravity

ABBREVIATIONS

ARINC	Aeronautical Radio, Incorporated
ATA	Air Transport Association
DOC	direct operating cost
GFAE	government furnished aeronautical equipment
IOC	indirect operating cost
LGS	landing guidance system
MLS	microwave landing system
MTBF	mean time between failures
PFCS	primary flight control system
SCW	supercritical wing
SID	standard instrument departure
STAR	standard terminal approach route
VHF	very high frequency
VORTAC	VOR and TACAN on a common site

ABSTRACT

Investigations were conducted to evaluate the relative benefits attainable through the exploitation of advanced technologies and to identify future research and development efforts required to permit the application of selected technologies to transport aircraft entering commercial operation in 1985. Results show that technology advances, particularly in the areas of composite materials, supercritical aerodynamics, and active control systems, will permit the development of long-range, high-payload commercial transports operating at high-subsonic speeds with direct operating costs lower than those of current aircraft. These advanced transports also achieve lower noise levels and lower engine pollutant emissions than current transports. Research and development efforts, including analytical investigations, laboratory test programs, and flight test programs, are required in essentially all technology areas to achieve the potential technology benefits.

SUMMARY

The research and development requirements generated during the course of this study fulfill the objectives of NASA in identifying actions required to accelerate specific technologies with large potential benefits and those where weaknesses are in evidence. Benefits in performance and economics of long-range transports are demonstrated by the application of advanced composite materials, supercritical airfoils, and active controls. Technology gaps and weaknesses are also identified for large structures containing a high utilization of advanced composite materials, the interference of wing-mounted nacelles and pylons with supercritical wings, and transonic aircraft design methodology. The emphasis on the achievement of noise levels 10 and 20 EPNdB below FAR 36 criteria has identified technology gaps in the prediction of the far-field aerodynamic noise of advanced transport configurations, in the achievement of lightweight acoustically treated engine nacelles, and in the validation of noise alleviation by means of flight operational techniques. In accordance with the above considerations, the following high priority tasks have been identified:

(1) Design, build, and test a full-size section of a typical advanced transport composite wing box.

(2) Design, build, and test a full-size barrel section of a typical advanced transport composite fuselage.

(3) Nacelle-wing interference at transonic speeds.

(4) Far-field aerodynamic noise evaluation.

(5) Design, build, and flight test a lightweight acoustically treated engine nacelle.

(6) Transonic design and analysis methods.

(7) Aircraft operational techniques for noise alleviation.

The schedule and funding for the above high-priority tasks are given in Figure S-1, covering the time frame of FY 1973 through FY 1980. Total program costs are given in Figure S-2 and are illustrated graphically in

Task \ FY	1973	1974	1975	1976	1977	1978	1979	1980	Total	Technology category
1. Composite wing box	0.600	1.900	3.000	1.000	0.800	0.800	0.800	0.800	9.700	Materials
2. Composite fuselage section	0.700	1.600	3.500	1.800	1.300	1.300	0.600	0.600	11.400	Materials
3. Nacelle-wing interference	0.200	0.300	1.000	1.200	0.400	0.200	0.100		3.400	Supercritical
4. Far-field noise	0.200	0.025							0.225	Noise
5. Lightweight acoustic nacelle	0.340	0.660	1.000	1.500	2.500	1.500			7.500	Noise
6. Transonic design and methods	0.500	0.600	0.700	0.800	0.800	0.600	0.500		4.500	Supercritical
7. Operational techniques--noise		0.150	0.300	0.150					0.600	Noise
* Cost benefit size effects	0.175								0.175	Systems
Total	2.715	5.235	9.500	6.450	5.800	4.400	2.000	1.400	37.500	

Figure S-1. Program costs in millions of dollars for priority one tasks.

Technical category	Fiscal year								Total
	1973	1974	1975	1976	1977	1978	1979	1980	
1 Advanced materials	2.825	5.495	9.495	5.120	3.670	2.170	1.470	1.470	31.715
2 Supercritical technology	1.270	1.910	2.695	2.795	1.465	0.800	0.600		11.535
3 Noise reduction	0.865	1.635	1.900	2.100	2.710	2.025	0.025		11.260
4 System studies	0.595	3.360	4.855	6.680	4.000	3.000	2.000		24.490
5 Active controls	0.380	0.185	0.540	0.300					1.405
Totals	5.935	12.585	19.485	16.995	11.845	7.995	4.095	1.470	80.405

Figure S-2. Total program costs in millions of dollars.

Figure S-3. In these figures, the research and development tasks are divided into five technology categories. The total cost of all programs shown is $80.405 million. Of this total cost, advanced materials account for $31.715 million or 39.4%, systems studies account for $24.490 million or 30.5%, noise reduction accounts for $11.260 million or 14.%, and supercritical aerodynamics accounts for $11.535 million or 14.3%.

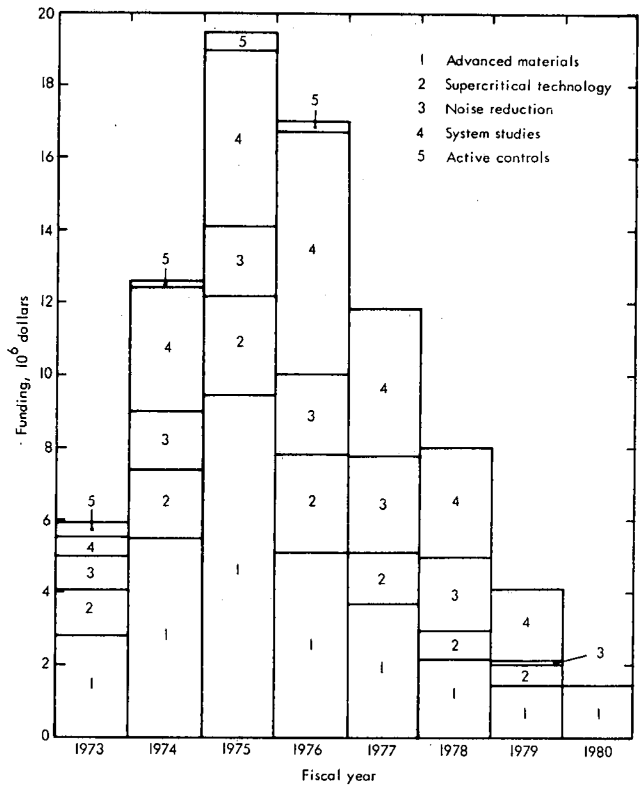

Figure S-3. Program cost summary.

1.0 INTRODUCTION

The objectives of the study described in this report include both the evaluation of the relative benefits attainable through the exploitation of advanced technologies and the identification of future development efforts required to permit the application of selected technologies to aircraft entering the commercial transport fleet in 1985.

The studies addressing the first of these objectives are described in Volume I, "Analysis and Design." In Volume I, the parametric analyses, engineering investigations, and design studies conducted in assessing the impact of advanced technologies are discussed and the resulting advanced technology benefits are evaluated.

The second study objective is the subject of Volume II, "Research and Development Requirements." This volume identifies the future programs required to realize the advanced technology benefits outlined in Volume I.

The research and development tasks which have been identified are categorized according to technology area in Sections 3.0 through 8.0, which follow. In each technology area, the required tasks are evaluated relative to state of readiness and priority, and programs are formulated which are compatible with the production commitment of the technology in 1980, as required for initial passenger operation in 1985. Estimates of funding requirements by fiscal year are included.

Sections 9.0 and 10.0 of this volume are devoted to aspects of the research and development requirements which are common to all technology areas. In Section 9.0, a program plan is developed for the completion of first priority laboratory and flight test programs. This plan includes consideration of interdependencies among the tasks and outlines schedules and costs which ensure the availability of data as required through the sequence of programs leading to the production commitment of the technologies. In Section 10.0, requirements for new developmental equipment are described.

2.0 CRITERIA

The research and development tasks presented in Sections 3.0 through 8.0 of this volume are described with the aid of technology readiness ratings and priority ratings. The assumptions on which the ratings are based and definitions of the ratings are given below.

2.1 READINESS RATING

Technology readiness ratings, based on the technology status as of January, 1972, are defined as follows:

1. Technology is sufficiently well defined to permit production commitment.

2. Technology is reasonably well defined. Additional development is required, with a high probability of near-term success.

3. Technology is not well defined. A significant amount of additional development is required to correct technological deficiencies. Basic research may be required in some cases.

2.2 PRIORITY RATING

The establishment of priority requires specification of both an objective and the time frame within which the objective must be realized. For the purposes of this study, the objective is assumed to be the realization of the technology benefits outlined in Phase II, Section 7.0 of Volume I. The time frame is established by the assumption that the technologies must be ready for production commitment in 1980. Based on these assumptions, the following priority ratings are defined:

1. The task is fundamental to the achievement of the technology benefits described in Volume I of this report. The required technology will not be ready for production commitment in 1980 without a major effort.

2. The task is fundamental to the achievement of the technology benefits described in Volume I of this report. The required technology will probably be ready for production commitment in 1980 as a result of currently planned programs.

3. The task will contribute significantly to the development of an advanced technology transport aircraft, but is not fundamental to the achievement of the technology benefits described in Volume I of this report.

3.0 DESIGN

3.1 STATE OF THE ART

The achievement of the design goals established during the course of this study is dependent on the proper direction of research and development effort to meet a production commitment date of 1980.

The success of a commercial airplane design depends largely upon the economic returns in a revenue-producing environment, which can be related to the useful load fraction of the design. The useful load fraction, in turn, is dependent upon structural, aerodynamic, and propulsive efficiencies.

The impact of materials and supercritical wing technologies is particularly critical to the development of the next generation of long-range, high-subsonic transport aircraft. These technologies must be developed to the point of production availability, although it must be recognized that a variety of problems are involved in achieving the projected technology benefits. Commitment to design will require the availability of the detailed knowledge of design procedures, materials properties, and fabrication technologies. The development of new skills and improved planning, testing, and data acquisition methods will be necessary if the benefits of the new materials are to be achieved.

Aerodynamic supercritical airfoil technology improves the structural weight characteristics of the wing primary structure due to an increase in wing thickness at a given Mach number. At the same time, the increase in trailing-edge loading over conventional sections and the reduction in trailing-edge thickness, together with an increase in camber, imposes severe design constraints on the integration of trailing-edge devices.

The structural efficiency of the fuselage shell is impaired when provision is made for doors and windows. The elimination of some or all of the windows could increase structural efficiency and improve weight characteristics. The elimination of windows is a human factors problem which requires attention before this problem can be resolved.

The problems associated with size must be addressed, particularly with regard to the manufacture of components. The proposed M = 0.95 airplane assumes that the production capability exists to handle composite structures up to 90 ft (27.4 m) in length and 10 ft (3.05 m) in width.

Considerable experimentation is required to determine the behavior and characteristics of large composite materials structures with regard to thermal effects. The development of adhesive processes not requiring the application of heat may be significant to the practical application of these materials.

Limited areas of retrofit appear possible in a number of areas such as the application of lightweight composite structures to landing gears and the development of lightweight acoustically-treated nacelles.

3.2 R&D TASKS

Recommended R&D tasks in the area of design and a summary of the corresponding funding requirements are given in Table I and Figure 1, respectively. Detailed task descriptions, including funding and schedule requirements, are given in Sections 3.2.1 through 3.2.12.

TABLE I. TASK SUMMARY - DESIGN

Task	Readiness rating	Priority	Type: Study	Type: Lab test	Type: Flt test	Retrofit	NASA support
Design, build, and test a lightweight acoustically-treated nacelle	2	1	X			Yes	Yes
Cost benefit study of size effects for a flight demonstration vehicle	2	1			X	Yes	Yes
Composite materials design philosophy	2	2	X			No	Yes
Integration of trailing-edge devices and engine nacelles into wing	2	2	X			No	Yes
Development of passenger and cargo accomodations	2	2	X			No	Yes
Design main landing gear using composite materials	3	2	X			Yes	Yes
Design of composite supercritical transport-type wing for flight testing	2	2		X	X	Yes	Yes
Landing gear wheel drive system	3	2	X			No	Yes
Application of air-cushion landing gear	3	3	X			No	Yes
Acceptability of windowless passenger cabin	1	3	X			Yes	Yes
Design of advanced control systems for transonic transport	2	3	X			No	Yes
Structural design concept study	2	3	X			No	Yes

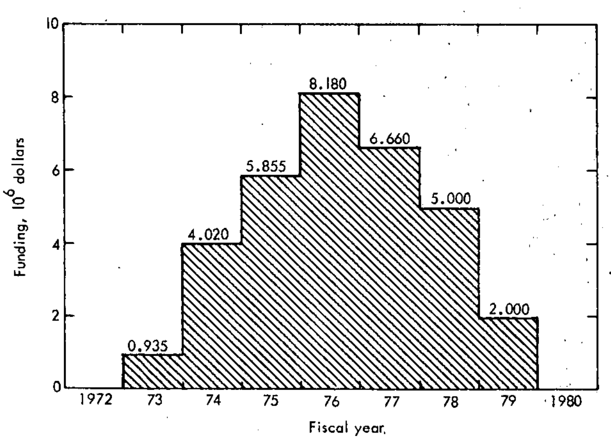

Figure 1. Funding summary - Design.

3.2.1 Design, Build, and Test A Lightweight Acoustically-Treated Nacelle

Area: Design

Objective: The objective of this program is to design, build, and test integrated acoustic-composite nacelles capable of meeting the noise level objective of FAR 36-15 EPNdB. Using nacelle contours developed for application to the $M = 0.95$ configuration, emphasis will be placed on combining acoustic liner and composite structural materials. Every effort will be made to assure a practical installation directly applicable to production usage in advanced technology aircraft.

Scope: A three-phase program, extending for six years is planned for this study. The first phase includes analysis, component laboratory tests as required, and detailed nacelle design. The second phase consists of fabricating a boilerplate nacelle and performing the static test stand portion of the program. Fabrication of four flight-weight nacelles and the completion of a flight test series constitutes the third and final phase of the program. Test engines will be supplied as GFAE by the NASA.

Approach: The initial task will be to perform preliminary analyses and identify the areas requiring further component development. Tests will be planned to establish minimum technology levels for these cases. Results from these tests will be integrated into the detailed design work already under way. The first nacelle design completed will be an aerodynamically and acoustically engineered boilerplate configuration. Fabrication and early testing will precede the building of any flight hardware. The program will include static performance, noise, fatigue, and compatibility tests. When reasonably satisfactory results are obtained, fabrication will begin on the flight hardware. The flight program will include complete tests to determine certification noise levels, as well as tests to evaluate compatibility and performance. The operation of anti-icing, drainage, and cooling systems will be studied. Maintenance requirements of acoustic liners will be determined.

Results and Potential Benefits: Successful completion of this program will provide an accurate picture of the improvement potential, as applied to nacelles, in the areas of weight, performance, and noise. Tradeoffs will be made using cost comparisons with conventional nacelles. The effects of vibration, sonic fatigue, and wide ranges of temperature will be documented. The practicality of combining acoustical treatment with composite structure will be determined. Compatibility of acoustical treatment with internal engine aerodynamics will be evaluated in detail. The development of at least one version of an advanced technology

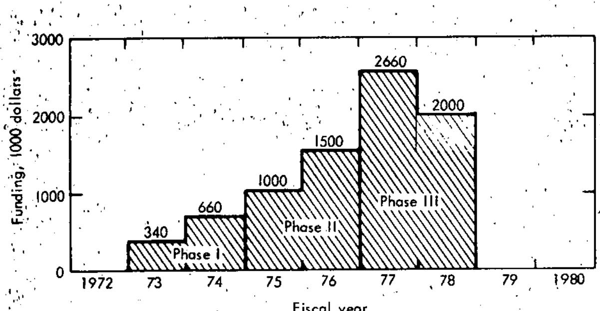

Figure 2. Funding required – Design, build, and test a lightweight acoustically treated nacelle.

prototype nacelle will be completed and, with little modification, could be utilized in a practical production installation.

Facilities: A large experimental shop to house the flight vehicle will be required.

Funding: Funding requirements for this task are shown in Figure 2.

3.2.2 Cost Benefit Study of Size Effects For a Flight Demonstration Vehicle

Area: Design

Objective: To assess the meaningful test data which can be obtained from research aircraft of various sizes designed to simulate pertinent characteristics of advanced technology transport aircraft, and to estimate costs of such aircraft.

Scope: Aerodynamic, structural, dynamics, propulsion, and control systems analyses will be performed to evaluate the degree of simulation possible for specific research tasks.

Approach: The fundamental design parameters of research aircraft will be studied in relation to the degree of simulation of large transonic transport aircraft. Relative values of size, mass, flexibility, control system dynamics, and flight condition will be adjusted to improve this simulation. Special attention will be given to aerodynamic, flight dynamics, aeroelastic, noise, and materials research tasks which might be accomplished with such aircraft.

Results and Potential Benefits: By assessing the useful research information obtainable from flight tests of aircraft scaled as indicated above, in relation to the cost of design and fabrication of such aircraft, the minimum-cost airplane required to accomplish given tasks can be defined.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 3.

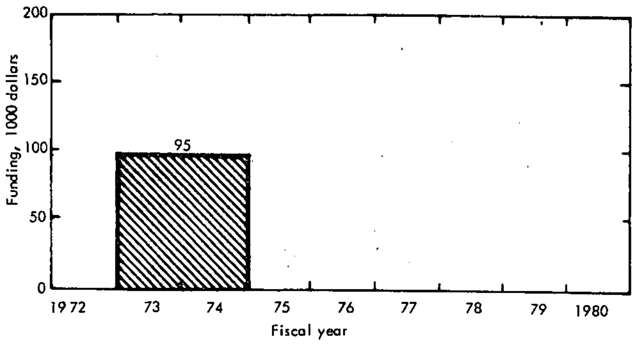

Figure 3. Funding required – Cost benefit study of size effects for a flight demonstration vehicle.

3.2.3 Composite Materials Design Philosophy

Area: Design

Objective: To determine the proper scheduling relationship of test programs, engineering, manufacture, and flight testing for application to production airplanes designed for high utilization of composite materials.

Scope: Design concepts for composite structures, including materials mix, will be considered to ensure compatibility. Assessment of tooling and manufacturing methods and skills required will be included.

Approach: Historical data relating to scheduling used in past programs will be analyzed to determine the phasing of test and experimental data relative to engineering, manufacture, and flight test segments of these programs. The impact of using estimated data with later test verification upon design and design changes will be determined for translation into design concepts for composite materials.

Results and Potential Benefits: The study will provide a design philosophy based on past experience, extrapolated to new design concepts using composite materials and other technology advances, to ensure the proper interdisciplinary relationship required to meet program goals.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 4.

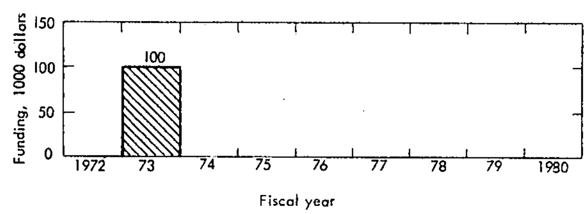

Figure 4. Funding required – Composite materials design philosophy.

3.2.4 Integration of Trailing-Edge Device and Engine Nacelle Into Wing

Area: Design

Objective: To determine the optimum trailing-edge high-lift device for the M = 0.95 study airplane. Nacelle locations and pylon shapes will be determined, as well as solution of structural requirements for high-lift system, nacelles, and pylons.

Scope: In-depth analysis of the M = 0.95 configuration flap system and engine-nacelle-pylon integration, based on results of tests and engine studies. The analysis will include jet efflux proximity to lower surface, impingement on deflected flaps, and acoustic effects.

Approach: Using the flap and engine nacelle arrangement developed during the current study as a baseline, flap system loads will be determined and a system designed to meet the stringent requirements of the airplane. Effects of wing distortion, span load continuity with flaps deflected, manufacturing tolerances on slats and caps, and engine nacelle location will be included. Engine data from the engine contractors will be used.

Results and Potential Benefits: The study will provide an accurate assessment of wing/flap/nacelle-pylon integration weight penalties, the effects of jet efflux on wing and flap design, configuration, and materials, plus determination of the effects of distortions occuring to a supercritical wing on flap system/nacelle design.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 5.

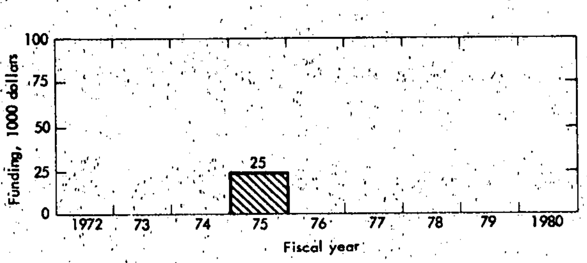

Figure 5. Funding required – Integration of trailing-edge devices and engine nacelles into wing.

3.2.5 Development of Passenger and Cargo Accommodations

Area: Design

Objective: To generate human engineering concepts for flight-station integration, passenger service and comfort, and cargo-baggage on-board handling.

Scope: This study will be limited to the development of designs to solve current aircraft interior problems and incorporate the advanced features considered feasible and desirable by the airframe and airline industries.

Approach: Using the area-ruled body developed for the M = 0.95 baseline configuration and analyses of current aircraft interior problems, perform design studies to maximize use of body volume created by area-ruling. Design schemes will be sought by which current passenger comfort levels and cabin crew efficiency can be upgraded. Problems such as crowded seating and inadequate galley or buffet facilities can undoubtedly be solved or greatly lessened by proper use of additional cabin volume. Body shape and volume studies of the underfloor cavities will serve to improve on-board cargo-baggage handling. Human engineering and cockpit integration studies will be aimed at reducing pilot work load and increasing safety while considering the impact of steeper glide slopes and congested terminal areas.

Results and Potential Benefits: The study will produce design guidelines acceptable to the ultimate airline operators for flight-station arrangements using advanced instrumentation and techniques, improved passenger comfort levels, cabin crew efficiency, and advanced concepts for on-board cargo-baggage handling. Human engineering mockups as required to verify proof of concept in interior arrangements will be produced.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 6.

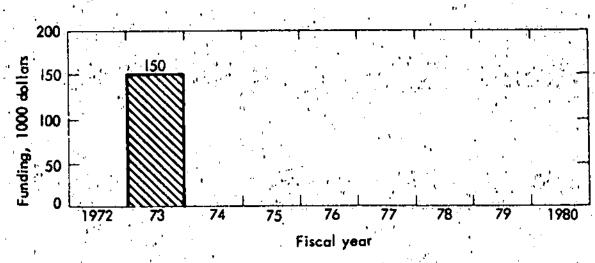

Figure 6. Funding required – Development of passenger and cargo accommodations.

3.2.6 Design Main Landing Gear Using Composite Materials

Area: Design

Objective: To determine the feasibility of manufacturing a landing gear strut from composite materials in order to realize the weight savings accruing thereto.

Scope: Explore the possibilities of using composite materials for fabricating the major components of a multiple-strut main landing gear. Based on these findings, design a gear, identify the manufacturing skills and facility items required, and perform drop tests, static tests, and flight tests.

Approach: Exploit the lightweight characteristics and flexibility of materials usage to determine the requirements and techniques required to design and fabricate a landing gear from composites, and/or composites and metals in combination.

Results and Potential Benefits : Design criteria, design techniques, and test data required to make use of composites in the design and fabrication of mechanical items such as landing gear.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 7.

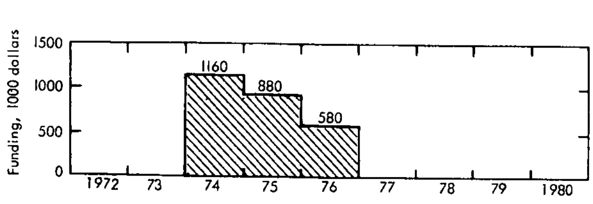

Figure 7. Funding required - Design main landing gear using composite materials.

3.2.7 Design Of Composite Supercritical Transport-Type Wing For Flight Testing

Area: Design

Objective: To verify the structural integrity of a wing box constructed of composite materials.

Scope: Design and fabrication program for a scale-model wing for flight test.

Approach: Using the M = 0.95 baseline configuration, a wing box to the appropriate scale for adaptation to the NASA F-8 test airplane will be designed and built. The wing-box design will incorporate the features necessary to simulate a transport wing design as closely as practicable within the size constraints.

Results and Potential Benefits: A flight specimen of a composite supercritical wing box for flight test to verify the structural integrity, determine the maintainability problems, establish repair procedures and techniques, and determine operational serviceability characteristics.

Facilities: Composite materials manufacturing equipment.

Funding: Funding requirements for this task are shown in Figure 8.

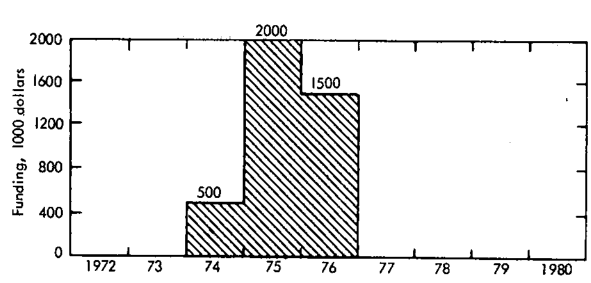

Figure 8. Funding required - Design of composite supercritical transport-type wing for flight testing.

3.2.8 Landing Gear Wheel Drive System

Area: Design

Objective: To provide a comparison between the use of powered-drive main-landing-gear wheels and engine power for maneuvering aircraft in and around airports.

Scope: The study will include investigations and testing to determine the feasibility of applying a wheel-drive concept to the main landing gear using auxiliary power sources. The study will consider landing-gear/system-integration; effects on bogie-axle brake design, weight, performance, and airplane costs; and operating economics.

Approach: The main landing gear configuration of the M = 0.95 study aircraft will be taken as the baseline, and a power-driven gear designed. Design conditions will be established analytically and configurational changes will be made where required. Weight, performance and economic estimations will be based on the same criteria as were used for the original M = 0.95 configuration. Following preliminary studies, a test program will be initiated in which a powered wheel-drive system for a medium-sized jet transport will be designed, fabricated, installed, and tested.

Results and Potential Benefits: The study will provide design, weight, operational, and comparative economic data. Configuration integration, materials, and design criteria will be established.

Facilities: None.

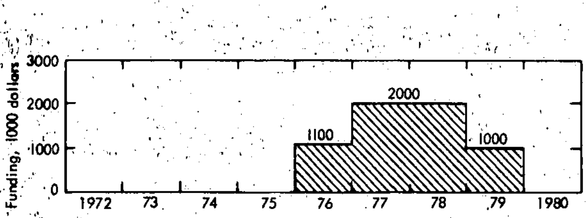

Figure 9. Funding required – Landing gear wheel drive system.

Funding: Funding requirements for this task are shown in Figure 9.

3.2.9 Application of Air-Cushion Landing Gear

Area: Design

Objective: To provide a comparison between conventional and air-cushion landing gear and establish a criterion for selection of gear from practical and economic viewpoints, and to provide fabrication, integration, and operational test data.

Scope: Investigation of the feasibility of applying an air-cushion landing gear to the M = 0.95 configuration, considering the practical aspects of airframe-design/landing-gear/ propulsion-system integration and the effects on weight, performance, airplane cost, and operating economics, and the application of such a system to a current jet transport to gain operational test experience.

Approach: Using the M = 0.95 configuration as a base, the preliminary design of an air-cushion gear will be accomplished. Design conditions will be established analytically and airplane configuration changes will be made as required. Weight, performance, cost, and economic estimations will be based on the same criteria as used for the M = 0.95 study airplane. Comparative data for a conventional landing gear will be established. An air-cushion gear will be designed, fabricated, and tested on a current jet aircraft to establish design, fabrication, and operational criteria.

Results and Potential Benefits: The study will provide a comparative basis for selecting a gear for the airplane, including the materials, configuration changes, and the practical aspects related to air-cushion gears.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 10.

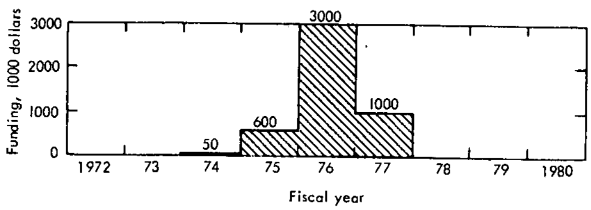

Figure 10. Funding required - Application of air-cushion landing gear.

3.2.10 Acceptability of Windowless Passenger Cabin

Area: Design

Objective: To determine from the flying public their reaction to and acceptability of a windowless passenger cabin.

Scope: Analysis of passenger reactions to determine the general acceptance level of making reasonably long flights in a windowless passenger cabin. Study feasibility of installing decorative panels to replace windows.

Approach: With the cooperation of an airline flying military charter flights, blank out existing cabin windows, using trim panels in their place. Gather data on passenger reaction by observation and questionnaire. Analyze human factors data collected for presentation to commercial carriers to solicit their opinions.

Results and Potential Benefits: This study will provide a valid human-factors data base of public opinion regarding public acceptance of windowless cabins. These data form the basis for tradeoffs between passenger acceptance and potential economic benefits derived from weight-saving available through window deletion.

Facilities: Use of one or two passenger airplanes in normal operations in charter service.

Funding: Funding requirements for this task are shown in Figure 11.

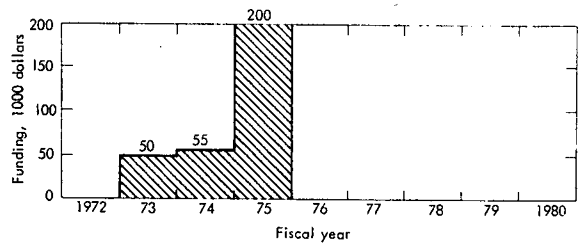

Figure 11. Funding required - Acceptability of windowless passenger cabin.

3.2.11 Design and Test of Advanced Control Systems for Transonic Transports

Area: Design

Objective: To perform detail design and test of control systems for the M = 0.95 configuration.

Scope: Component requirements will be developed based on system synthesis. Detail designs will be prepared, parts and subsystems will be fabricated, and the system will be tested. Since most of the components involved are normally vendor-supplied, contacts and coordination with component vendors will be established for a prototype system.

Approach: Analyze problems of advanced control system components resulting from the severely restricted space limitations dictated by the supercritical airfoil sections and complexity imposed by a high degree of redundancy. Component requirements will be determined as dictated by applied loads, ride quality, artificial stability, flutter, temperature, and operation. The M = 0.95 supercritical airfoil system will be designed and scaled as required for installation into a current jet aircraft for test operations. A system will be fabricated, ground tested, and flight tested. Wing high-lift devices, ailerons, rudder, elevator, flying tail, asymmetry detection devices, high-speed higher-pressure hydraulic pumps and systems, torque-drive units, and flutter suppression units will be considered and included as required in the design for the test system.

Results and Potential Benefits: Design criteria for transonic transport control systems and components from a broad base developed from system synthesis, detail design, fabrication, and ground and flight tests.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 12.

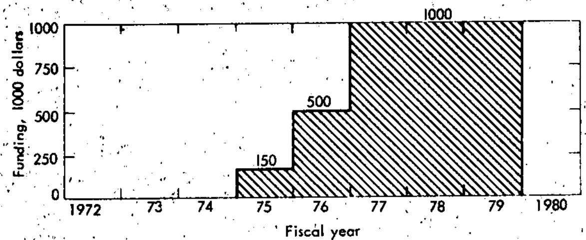

Figure 12. Funding required – Design of advanced control systems for transonic transport.

3.2.12 Structural Design Concept Study

Area: Design

Objective: To determine the feasibility, weight, and cost of unconventional design concepts as applied to composite aircraft construction.

Scope: Explore the possibilities offered by various unconventional structural concepts such as curved spar and stringers at swept wing roots; multi-diagonal-spar "ribless" wings; surface panels with integrally molded stringers and rib ties, etc. Methods of repairing damaged composite bonded assemblies will be included.

Approach: Using the M = 0.95 configuration as a baseline, examine the structural concepts in sufficient detail to establish design feasibility, structural integrity, weight, and cost. Determine the comparative weight and cost data for the various concepts and the economic impact on the airplane. Detail design and fabricate a half-wing structural test specimen of the concept selected from the economic studies. Static test the specimen to verify strength and fatigue criteria used. Develop methods to accomplish damage repair for primary structural composite components.

Results and Potential Benefits: The study will result in an optimized structural arrangement for the aircraft with comparative weight and cost data; design, fabrication, and structural criteria verification by testing; and practical methods of repairing damaged composite structures.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 13.

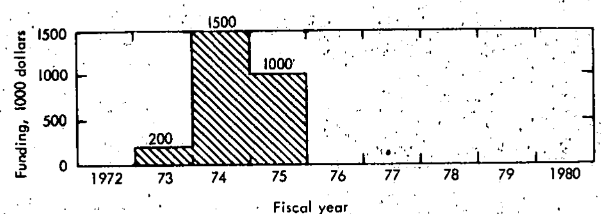

Figure 13. Funding required – Structural design concept study.

4.0 AERODYNAMICS

4.1 STATE OF THE ART

The aerodynamic development of any aircraft depends heavily on an intimate interplay among several design and development processes. In early stages of a program, only engineering and design functions are involved. However, overall program schedules require that tooling and manufacturing efforts begin before final developments in aerodynamics and other technical disciplines are completed. Phasing of these functions is illustrated in a simple manner in Figure 14. The pacing of development in the technical disciplines is directly proportional to the facility with which accurate predictions can be made of the effects of variations encountered in any of the disciplines as the total airplane is evolved. The R&D effort devoted to improvement in the precision of predicting aerodynamic characteristics of given configurations, or of developing the configurations which will achieve optimum characteristics, therefore has tremendous leverage on the outcome of the total development program.

The initial concept of a new airplane design is usually based on a partially developed set of technological information. In some cases this might be a theoretical concept by which optimum aerodynamic shapes and their characteristics can be described analytically, but with an incomplete experimental demonstration of their achievability. In the case of supercritical aerodynamic information, the experimental demonstration of efficient cruise performance at Mach numbers very close to unity is in hand, but the analytical capability to describe aerodynamic shapes for a new configuration which will attain a comparable level of cruise performance is not well established. Current practice generally relies upon experimentally demonstrated correlations between the subcritical velocity distribution about a given aerodynamic shape, and the desirable supercritical velocity distribution for that same shape at higher Mach numbers. Using these concepts for the initial design of a wing, combined with a fuselage, empennage, and engine pods in such a way as to build up an acceptable total area distribution, with each of the components designed to be an efficient shape, provides the first approximation to an acceptable aerodynamics configuration. Development of a final configuration then depends upon wind-tunnel testing, with the measurement of sufficient detailed aerodynamic information to diagnose the cause of any deviation from the design characteristics. Recognition of the source of the discrepancy permits the application of proper corrective changes to the aerodynamic contours based on empirical or analytical knowledge of the effects of such contour modifications.

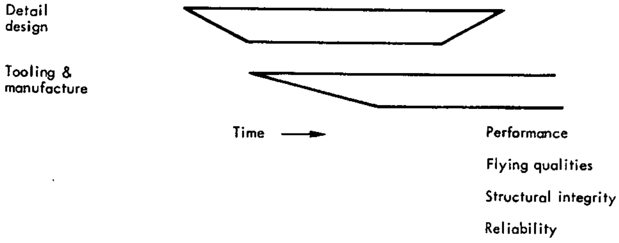

Figure 14. Development phasing schedule.

While the example just cited relates to supercritical aerodynamics, the same process is required to develop acceptable aerodynamic characteristics for any flight regime for which there does not exist an aerodynamic theory adequately describing the significant flow properties, plus a sufficient amount of experimental data to substantiate the theory and to define the limits of its applicability. The effects of this incomplete status of aerodynamic information produce significant impacts on an airplane development program in several ways:

(1) Increased time and cost for experimental development.

(2) Program delays to accomplish configuration refinement.

(3) Possible revision of tooling and scrappage or rework of fabricated parts.

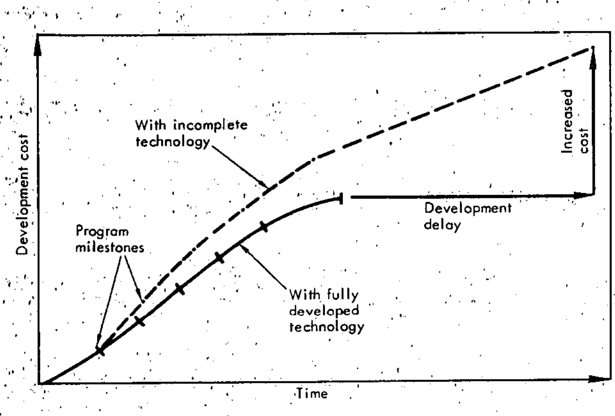

Figure 15. Typical effect of delays to program cost and schedule.

These effects are illustrated by the curves shown in Figure 15. Each failure to reach an established program milestone due to difficulty in achieving projected characteristics results in additional efforts on that task and frequently requires repetition of subsequent tasks which have been based on the projected characteristics. The magnitude of the impact of each such event increases with time since a larger number of completed tasks are affected. The cumulative effect is an increase in both cost and time span for the development program and quite properly could result in additional costs due to penalties for late deliveries.

The significance of the following recommendations for additional research and development efforts in aerodynamics must be judged in consideration of the required capability to derive configurations which will achieve optimum characteristics and to assess the effects of configuration modifications, as well as their direct effect on improved performance.

4.1.1 Transonic Aerodynamics

Economic studies presented in Volume I of this report show that the return on investment for an airplane designed to cruise 5500 n.mi. (10 186 km) at 0.95 Mach number with 400 passengers is increased by approximately 6% by incorporation of the supercritical wing. Additional benefits accrue, however, in such areas as buffet margin, and the reduction of problems in achieving high takeoff and landing maximum lifts. These factors do not influence economic analyses significantly. As indicated previously, the supercritical aerodynamic development already accomplished has demonstrated the capability of cruise at Mach numbers very close to 1.0. The outstanding task remaining is to attain the aerodynamic design ability to develop configurations for arbitrary mission requirements and for rapid assessment of the detail aerodynamic characteristics for such configurations. Results of tests conducted in the contracted Parametric Optimization Test Program have shown that a reduction in size of the inboard wing glove of a supercritical wing can improve pitching moment linearity at high lift coefficients with some sacrifice in zero-lift pitching moment. In the absence of analytical tools to evaluate changes such as these, experimental programs and accompanying configuration studies are required to permit wing planform geometry optimization.

The strong lateral propagation of disturbances at near-sonic speeds invalidates many aerodynamic approximations which have proven extremely useful at lower speeds. Strip theories or lifting-line theories for evaluating aeroelastic effects are outstanding examples. Accelerated effort, both analytical and experimental, are required to develop methods for these analyses.

The efficacy of the area rule in establishing overall configurations has been clearly demonstrated in the course of development of supercritical aerodynamic technology. The additional requirement that each component of an airplane configuration must have an efficient aerodynamic contour of its own sometimes conflicts with practical design considerations relating to pilot visibility or structural requirements such as flap-track fairings or enclosures for landing-gear stowage. Generalized experimental studies, accompanied by analytical consideration of results, can provide guidance for the design of these appendages and for the achievement of their sometimes beneficial side effects. For example, flap-track fairings have produced drag reductions in spite of their increased wetted area.

4.1.2 Transonic Wind-Tunnel Testing

Slotted or perforated wind-tunnel walls are satisfactory in eliminating or decreasing wall constraint effects at modest subsonic Mach numbers. Because of the extensive propagation of disturbances at near-sonic speeds, however, it is likely that new wind-tunnel test-section configurations will be required, or new sets of wall-induced corrections must be applied to wind-tunnel data. Studies are now underway by NASA to evaluate the severity of this problem. Great urgency must be attached to adequate solutions to these problems, since much of the aerodynamic information required for the development of advanced transports must be based on the results of wind-tunnel investigations.

Reynolds number effects have been shown to produce large changes in aerodynamic characteristics measured at transonic speeds for several existing transport aircraft. It would be expected that supercritical wings would be susceptible to similar effects due to high aft loading and rather flat supercritical Mach-number distribution. Existing basic data were obtained with transition strips on the model wing located to match the estimated flight boundary-layer thicknesses, and should therefore provide reasonable approximations of the flight flow condition for cruise conditions. The potential exists for discrepancies between wind-tunnel and flight results from two causes; significant differences in shock location due to differences in trailing-edge separation at high lift coefficient, and differences in development of the supercritical flow field resulting from differences in the growth of boundary layer thickness. Research is required to produce a better understanding of the complex flow phenomena leading to these results and to develop wind-tunnel test procedures and techniques for adequate full-scale simulation. Ultimately, wind tunnels with full flight Reynolds number capability will provide the only completely satisfactory method to investigate these effects. Current NASA and Air Force efforts to develop such facilities must be encouraged. An outstanding point which is sometimes overlooked in this regard is that currently existing wind-tunnel capability imposes certain limits on the improvement in transonic airplane development. Current practice generally demands that all significant flow separations be eliminated in wind-tunnel tests for cruise conditions at the test Reynolds number, which may be an order of magnitude less than the flight value. This procedure is necessary since the Reynolds number effect on separation cannot be predicted with confidence, and results in an inherent conservatism in the aerodynamic configuration development.

4.1.3 High-Lift System Development

The development of suitable high-lift systems for advanced technology transport aircraft presents problems which are, in many respects, unique to these aircraft. Planforms with inboard highly-swept gloves, thin after-portions of airfoil sections, and high sweep angles are all features which produce different effects from those which are rather well known for most current airplane configurations. Data presented in Volume I of this report show that significant reductions in aircraft size and cost to perform a given cruise mission can be achieved by increases in wing loading. Consequently, attainment of reasonable field lengths requires powerful high-lift devices. Reduction in community noise levels add to the incentive to high-lift system refinement. The ultimate benefits accruing to advanced technology aircraft from improvements in high-lift system performance appear in terms of both lower costs for the airlines and an improved acoustic environment for the airport neighbors.

4.2 R&D TASKS

Recommended R&D tasks in aerodynamics and a summary of the corresponding funding requirements are given in Table II and Figure 16, respectively. Detailed task descriptions, including funding and schedule requirements, are given in Sections 4.2.1 through 4.2.7.

TABLE II. TASK SUMMARY - AERODYNAMICS

Task	Readiness rating	Priority	Type			Retrofit	NASA support
			Study	Lab Test	Flt Test		
Transonic design and analysis methods	3	1	X	X		No	Yes
Pitching moment characteristics of supercritical wings	2	2	X	X		No	Yes
High lift system development for supercritical wings	2	2	X	X		No	Yes
Transonic wind tunnel test techniques	3	2		X		No	Yes
Reynolds number effects on supercritical wings	2	2		X	X	No	Yes
Aerodynamics data for aeroelastic analysis	2	2	X	X		No	Yes
Optimum design of protuberances for advanced technology transport	2	3	X	X		No	Yes

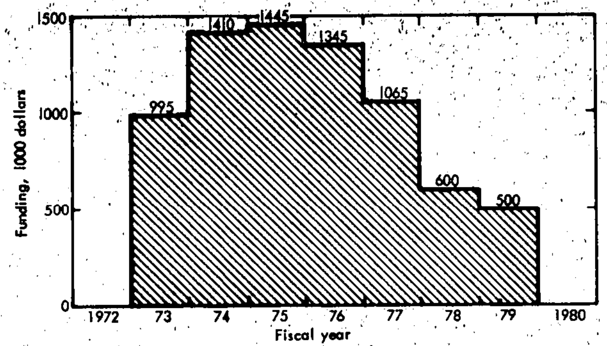

Figure 16. Funding summary - Aerodynamics.

4.2.1 Transonic Design and Analysis Methods

Area: Aerodynamics

Objective: (1) To expand and refine current semi-empirical methods for aerodynamic design of supercritical wings and wing-body combinations. (2) To develop aerodynamic design methods based on mixed subsonic/supersonic flow conditions.

Scope: Ultimate development of methods to attack this design problem with three-dimensional, mixed flow, wing/body considerations is likely to extend over several years. The two-phased objective noted above is required to permit immediate progress in supercritical aerodynamic development while continuing toward the final goal. Coordinated analytical and wind-tunnel investigations are required in both phases. Efforts on empirical methods should be phased out as mixed-flow techniques demonstrate useful design capability.

Approach: (1) Experimental studies to establish optimum location of cutouts to produce required area distributions and penalties associated with non-optimum area distributions, e.g., partially cylindrical fuselages. (2) Two-dimensional wind-tunnel tests, coordinated with calculations using existing methods to improve correlation and to optimize airfoil characteristics. (3) Accelerated development of promising mixed-flow computation methods aimed at the ultimate goal of designing optimum wing-body combinations recognizing practical constraints.

The complexity of this problem precludes the establishment of a straight-forward listing of tasks which will culminate in the desired capability. Several of the candidate mixed flow methods should be pursued until a concept emerges which can obviously be developed into a design procedure. This can best be accomplished by NASA coordination of efforts by several investigators, combined with appropriate wind-tunnel correlation studies.

Results and Potential Benefits: Successful completion of this program may result in small improvements in aerodynamic performance characteristics. The outstanding benefits will appear, however, in reduced wind-tunnel configuration development and in shorter and less costly overall development programs.

Facilities: Existing wind-tunnel and computer facilities.

Funding: Funding requirements for this task are shown in Figure 17.

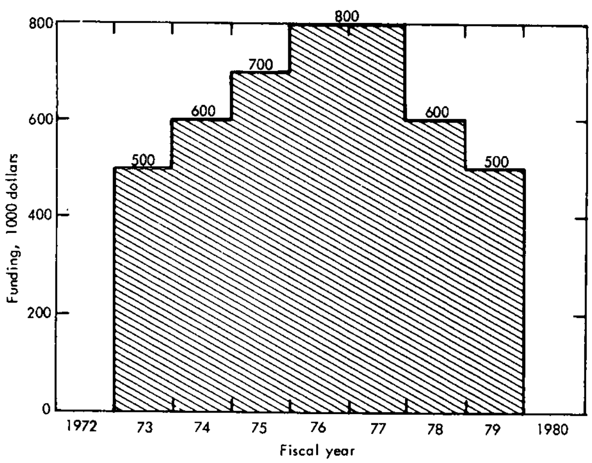

Figure 17. Funding required - Transonic design and analysis methods.

4.2.2 Pitching-Moment Characteristics Of Supercritical Wings

Area: Aerodynamics

Objective: To establish the trade-offs in transport airplane design associated with supercritical wing pitching-moment characteristics.

Scope: Wind-tunnel data will be obtained from tests of a model with a parametric variation of inboard glove designs. Utilizing the results of these tests, operating costs will be compared for aircraft designed with each of the configurations tested. These comparisons will show the trade-offs of potential changes in trim drag and parasite drag against improvements in pitching-moment linearity.

Approach: A series of four wings, all designed for cruise Mach number, but with variations in glove planform and camber, will be tested on a model representing a specific transport airplane design. Based on results shown by the parametric optimization program, changes in linearity of pitching-moment data, combined with changes in zero-lift pitching moment, can be anticipated. The source of these changes can be identified from pressure distribution measurements. Using the parametric sizing program, weight, parasite drag, and trim drag changes can be accounted for in establishing airplane configurations and operating costs for a given mission.

Results and Potential Benefits: Total airplane configuration optimization can be improved by recognition of the trade-offs outlined above. Deletion of a particularly complex SAS function can be accomplished if pitching-moment curves can be adequately linearized without significant penalty.

Facilities: Existing transonic tunnels.

Funding: Funding requirements for this task are shown in Figure 18.

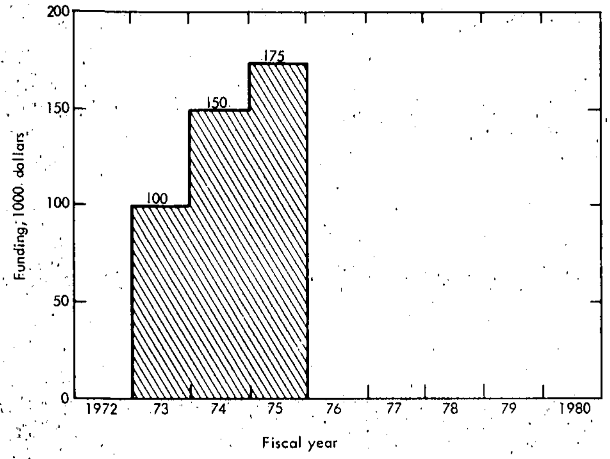

Figure 18. Funding required - Pitching moment characteristics of supercritical wings.

4.2.3 High—Lift System Development For Supercritical Wings

Area: Aerodynamics

Objective: To develop complete data on the aerodynamic characteristics of advanced technology aircraft with highly effective high-lift devices.

Scope: Analytical and experimental investigations should be conducted to define the low-speed performance, stability and control characteristics, and the downstream flow field for advanced technology transport aircraft, and to permit prediction of these properties for future aircraft having various design specifications.

Approach: Current NASA studies directed toward development of high-lift systems should be expanded in the following areas:

(1) Refinement of high-lift device geometry.

(2) Definition of the vortex-shedding characteristics of wings with highly-swept inboard gloves, and the effect on the flow field at rear-mounted engines and the empennage.

(3) Correlation of experimental versus calculated results.

Several analytical methods are in existence and can be used in the correlation process. Proper correlation of the experimental and analytical results would permit design of future aircraft with lower development costs.

Further benefits could be achieved in the development of advanced transport configurations if modest amounts of external blown-flap effect can be produced without increases in noise level. This subject is addressed in Section 6.0 of this volume.

Results and Potential Benefits: Direct benefits will be derived from increased maximum lift or lift-to-drag ratio which can be applied to improve operational economy through design for higher wing loadings at given field lengths, or to reduce field lengths and accompanying noise levels. Indirect benefits will accrue from improved capability to design configurations required to achieve a given level of performance and from a better definition of downstream flow fields.

Facilities: Existing low-speed wind tunnels.

Funding: Funding requirements for this task are shown in Figure 19.

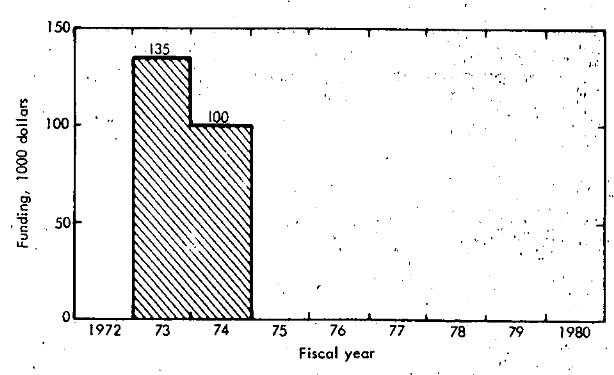

Figure 19. Funding required -High lift systems for supercritical wings.

4.2.4 Transonic Wind-Tunnel Test Techniques

Area: Aerodynamics

Objective: To develop wind-tunnel test techniques and/or test-section configurations suitable for obtaining data at M = 1.0.

Scope: Experimental investigations are required to demonstrate the feasibility of duplicating interference-free data by tests in transonic wind tunnels, or of correcting data for interference effects.

Approach: NASA has initiated investigations by drop model tests to disclose the nature of wall interference effects at near-sonic speeds. Results have shown substantial effects. Additional data are required for lifting conditions, and can be obtained from rocket models or from test-track investigations. Some studies have also been directed toward tailoring test-section walls to alleviate wall interference. These studies should be expanded to provide guidance for all near-sonic testing.

Results and Potential Benefits: Early completion of work in this area is required to permit proper assessment of the validity of existing data in this Mach number range, and to ensure that maximum benefits can be obtained from all the wind-tunnel investigations directed toward development of advanced technology aircraft.

Facilities: Existing transonic wind tunnels, rocket and drop model ranges, and test tracks.

Funding: Funding requirements for this task are shown in Figure 20.

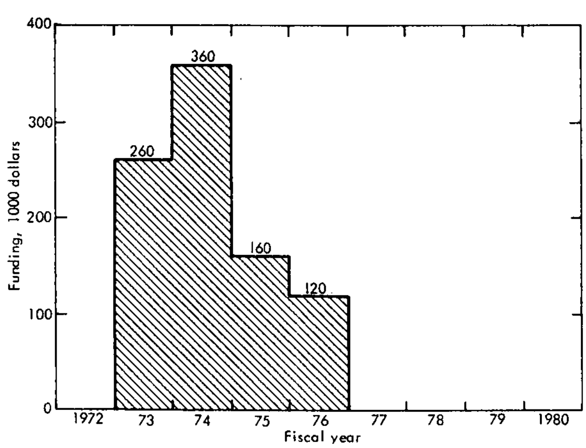

Figure 20. Funding required - Transonic wind tunnel test techniques.

4.2.5 Reynolds Number Effects On Supercritical Wings

Area: Aerodynamics

Objective: To demonstrate the character and magnitude of Reynolds number effects on supercritical wings and to establish appropriate methods for wind-tunnel simulation of flight characteristics.

Scope: Using a single aircraft configuration (the F-8 SCW or a new flight demonstrator), conduct wind-tunnel tests through a Reynolds number range from 2 million to 80 million for correlation against flight data and for predicting full-scale transport characteristics. Cruise drag, high-Mach-number/ high-lift-load distributions, and buffet characteristics should be considered.

Approach: Reynolds numbers up to 20 million can be attained by tests of semi-span models in several existing wind tunnels for correlation against flight data. Ludwieg tube tests can extend this Reynolds number range to about 45 million. Such tests can therefore bracket the flight Reynolds number for a demonstration airplane of the size of the F-8 SCW (12 to 25 million). Direct correlations can be established of pressure distributions, boundary-layer properties and overall aerodynamic characteristics between these two cases. The influence of surface condition can be evaluated, including the effects of manufacturing tolerances, which have a large impact on costs.

Wind-tunnel studies at lower Reynolds numbers, evaluated in relation to analytically derived predictions of Reynolds number effects can then be directed toward the development of proper simulation techniques for future development programs. This can be especially significant, since the majority of current transonic wind tunnels are limited in Reynolds number capability to 3 to 4 million.

Results and Potential Benefits: The direct results of this program will be a disclosure of the character and sources of Reynolds number effects, plus a refinement of wind-tunnel simulation techniques. These direct results will ensure a greater validity of all subsequent experimental technology development programs. In relation to a production airplane development program, inaccurate prediction of Reynolds number effects has the potential of a disastrous impact, since the final resolution of questionable predictions is obtained only by flight testing. Successful accomplishment of this program can eliminate the necessity for costly and time-consuming prototype programs for each new airplane.

Facilities: Existing and planned wind-tunnel facilities.

Funding: Funding requirements for this task are shown in Figure 21.

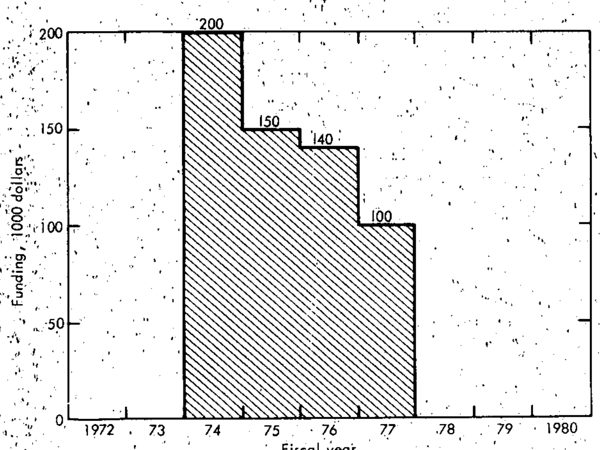

Figure 21. Funding required – Reynolds number effects on supercritical wings.

4.2.6 Aerodynamic Data For Aeroelastic Analyses

Area: Aerodynamics

Scope: Pressure distribution measurements are required for several supercritical wings having different shapes and magnitudes of spanwise twist distribution.

Approach: Rigid wind-tunnel model wings will be designed to represent a practical transonic transport configuration, and that same configuration with several twist distributions typical of distortions encountered in flight under different load conditions. Analyses of these results will permit the development of empirical methods for properly estimating aeroelastic effects. While it is not likely that simple superposition procedures, similar to those used at subsonic speeds, will be precise at near-sonic speeds, a first order approximation technique can probably be evolved. Results should also shed light on spanwise induction phenomena at supercritical speeds and provide useful check cases for three-dimensional analytical methods.

Results and Potential Benefits: Results from this program will provide immediate guidance for determination of stiffness requirements for supercritical wings, and should, by improving knowledge of spanwise induction effects, facilitate the development of three-dimensional production methods.

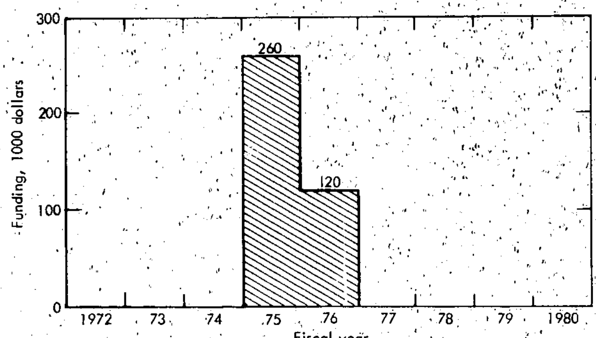

Figure 22. Funding required – Aerodynamic data for aeroelastic analyses.

Facilities: Existing transonic wind tunnels.

Funding: Funding requirements for this task are shown in Figure 22.

4.2.7 Optimum Design Of Protuberances For Advanced Technology Transports

Area: Aerodynamics

Objective: To provide concrete guidelines for the development of optimum aerodynamic shapes for aircraft protuberances which must respect non-aerodynamic constraints.

Scope: Two classes of protuberances, fuselage distortions such as windshields and landing-gear pods, and wing appendages such as flap-track fairings, must be considered. Experimental data on the effects of such protuberances, an identification of the basic phenomena leading to these effects, and correlation against an analytical accounting for those phenomena should be combined to produce a method for design of new aircraft.

Approach: Several existing methods permit the computation of pressure distributions on fuselages with complex shapes at subsonic speeds. Use of such a method would enable the design of a family of distorted fuselage shapes (with the distortions representing windshield panels providing acceptable vision, for instance). Wind-tunnel measurements of drag increment, pressure distribution, and flow characteristics, when correlated against the calculated results, will provide the basis for design of future comparable fuselage distortions and hopefully permit development of an optimization procedure.

In the case of appendages attached to wings, a better understanding of the phenomena leading to drag reductions is required. Having developed this understanding, a procedure similar to that above would be followed to evolve a design procedure.

Results and Potential Benefits: Significant reductions in development time, plus possible small performance reductions would accrue from the use of such design processes.

Facilities: Existing transonic wind tunnels

Funding: Funding requirements for this task are shown in Figure 23.

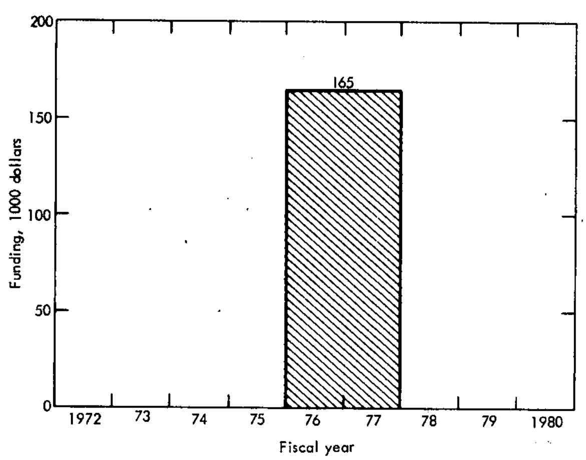

Figure 23. Funding required – Optimum design of protuberances.

5.0 STRUCTURES AND MATERIALS

5.1 STATE OF THE ART

Research and development programs are recommended for areas in structures and materials where deficiencies exist. Particular emphasis is placed on developing filamentary composite materials for transport aircraft. In Section 7.0 of Volume I, improvements were shown in the DOC and ROI for extensive application of composites to the primary structure, and major reductions were shown for the airframe weights. However, a major technology gap and lack of confidence exists for applying composites to the primary structure of a large, commercial transport. Deficiencies also exist in transonic data and methods for flutter analysis. Programs are included for measuring the pressures on oscillating supercritical wings and T-tails. The state of the art is discussed for each of the recommended research and development programs in the following sections.

5.1.1 Filamentary Composite Materials

Filamentary composite materials are currently being developed primarily for military fighters. Programs are underway to develop composite wing, empennage, and fuselage structures for the F-15, F-14, F-100, F-111 and others. Numerous secondary structural components have been built and placed on operational aircraft to accumulate service experience. The C-5 has eleven leading-edge slats flying and accumulating service experience at a rapid rate. Miscellaneous parts on other aircraft, including flaps, rudders, doors, horizontal tails, fairings, and ailerons are also accumulating service time. The only program to develop primary structure representative of a large transport is the C-130 boron-epoxy, reinforced-aluminum center wing box. The L-100, which is the commercial designation for the C-130, has internal surface loads and structural design requirements very close to those projected for the M = 0.95 study aircraft. The L-100 is an ideal vehicle for installing an all-composite center wing. It could provide the flight vehicle which would demonstrate primary, all-composite structure in a commercial transport and accumulate flight hours at a rapid rate in a commercial environment.

Composite material properties have been developed, and design guides have been published. The AFML Advanced Composite Design Handbook provides data for the preliminary design of composite parts. Programs have been developed for optimizing laminate lay-ups with composite materials, and the resulting physical properties and allowable strengths can be predicted for different ply orientations.

Material costs for graphite-epoxy are projected to be well within the range of eonomic feasibility by the 1980's. With additional development in manufacturing technology, the cost of an equivalent load-bearing structural component in composites could be less than the equivalent aluminum structural member.

There are, however, numerous risk factors which inhibit acceptance by designers, airlines and the FAA. Some are recognized deficiencies, such as brittleness and vulnerability to lightning strike. Other deficiencies relate to data and experience gaps, such as the effect of combined fatigue loading and environmental exposure upon matrix resins and thus upon mechanical properties of composites after long time exposure.

Ultimate confidence in composites can only be obtained by extensive ground testing and prolonged flight exposure. A large, commercial, long-range transport will be continuously exposed to repeated loads and operational environment at a utilization rate of approximately 4000 hours per year. The flight-load spectra, environment, and structural concepts will be entirely different from those of a military fighter. Few military aircraft accumulate flight time at the rate which is common for civil aircraft operations.

Since the utilization of advanced composites entails a degree of risk, it is imperative that ground testing of major structural components fabricated of composites be considered as early as possible. Programs are presented for full-scale sections of the M = 0.95 configuration wing box and the fuselage barrel.

From a national viewpoint, one can anticipate foreign competition against a U. S. transonic transport. The study has shown that heavy utilization of composites can reduce the physical size of the airplane and provide benefits in DOC and ROI. The DOC and ROI are sensitive to fly-away first costs. The higher raw-material costs of composites must be offset by reductions in costs of fabrication, tooling, assembly, and inspection. The design and development of the wing box and the fuselage test articles include developing concepts for economical production.

The recommended programs also include periodic NDT tests, including development of non-destructive inspection by methods such as determination of natural frequencies of the structures, and acoustic-emission readings under load as well as the more usual X-ray and ultrasonic examinations. Downstream in the program, damage tolerance and repair methods will be studied, and protection system against lightning strike will be evaluated.

The advantages of bonded structural joints are well known; bonding these joints, however, requires the use of an autoclave. Large assemblies, which cannot be placed in an autoclave, require special attention, especially on an airframe of the size under consideration. A task is included to develop adhesive material and process techniques for cold bonding to help solve this problem.

5.1.2 Lightning Strike And Electromagnetic Compatibility In Fiber-Composites

A commercial transport aircraft can expect, on the average, to receive one lightning strike per 3200 flying hours (Ref. 1). The consensus is that airplanes must be electrically continuous to provide lightning protection, electrical-system current-return paths, electrostatic charge dissipation, antenna performance, and electromagnetic interference control. Further research is necessary to develop optimized systems for aircraft constructed primarily of poorly-conducting materials to insure that lightning protection is adequate, electrical and electronic requirements are satisfied, costs are reasonable, and fabrication is feasible. Four tasks are included in this report to explore these areas.

5.1.3 Flutter-Prediction Technology

Deficiencies exist in several aspects of flutter-prediction technology with respect to advanced long-range transports. The most serious of these is the lack of adequate transonic oscillatory aerodynamic methods applicable to supercritical lifting surfaces. The current practice of utilizing subsonic (zero thickness) aerodynamic methods for flutter analysis in the high-subsonic flow regime, supplemented by transonic flutter model tests, has generally proven satisfactory for aircraft designed to operate with subcritical-flow lifting surfaces. The application of supercritical wing technology to advanced transports and the attendant increase in cruise Mach numbers into the transonic regime, coupled with the almost complete lack of knowledge of the transonic oscillatory aerodynamic characteristics of supercritical airfoils, however, increase the risk of the current approach to an unacceptable level.

In order to provide an early indication of the overall effect of supercritical airfoils on the transonic flutter characteristics of wings, transonic flutter model tests of a representative clean supercritical wing and a similar conventional wing should be conducted. Available static pressure data indicate that the flutter characteristics of supercritical wings may be strongly affected by steady lift. Investigations of these effects should be included in the flutter model tests.

Concurrent with the flutter model tests, a program should be initiated to develop an adequate transonic oscillatory aerodynamic method applicable to supercritical lifting surfaces. This method may take the form of empirical modifications to existing methods or a completely new formulation. Both approaches should be pursued.

In either case, the availability of high-quality oscillatory pressure data is essential for the evaluation and/or modification of the method. A wind-tunnel test program should be undertaken to measure such data on a representative supercritical wing model and should be followed by similar tests on a representative T-tail model.

Other deficiencies exist with respect to the development of active flutter- and modal-suppression systems for advanced long-range transports. Although not essential to the development of advanced long-range transports, such systems could produce significant benefits for some configurations. An area of great uncertainty with respect to application to supercritical lifting surfaces, however, is the reliable generation of the required oscillatory aerodynamic forces and moments in the critical transonic-flow regime. Therefore, tests should be undertaken to determine the effectiveness of both leading- and trailing-edge control surfaces for generating these forces and moments. Depending on the outcome of these tests, the effectiveness of a flutter-suppression system should be demonstrated by transonic flutter model wind-tunnel tests and full-scale flight tests. Also needed are the development of design criteria and synthesis techniques, e.g., by extension of the methods outlined in Reference 2.

5.2 R&D Tasks

Recommended R&D tasks in the structures and materials area and a summary of the

TABLE III. TASK SUMMARY - STRUCTURES AND MATERIALS

Task	Readiness rating	Priority	Type			Retrofit	NASA support
			Study	Lab test	Flt test		
Design, build and test a full size section of a typical composite wing box for a M = 0.95 airplane	2	1	X	X	X	Yes	Yes
Design, build and test a full size barrel section of a typical composite fuselage for a M = 0.95 airplane	2	1	X	X		No	Yes
Measurement of pressures on oscillating supercritical wing model	2	2	X	X			Yes
Measurement of pressures on oscillating supercritical T-tail model	2	2	X	X			Yes
Develop adhesive material for structural cold bond	2	2		X		No	Yes
Lightning versus composites overlaid on metal	2	2	X	X		Yes	Yes
Lightning probability modeling of all-composites aircraft	2	2	X	X			Yes
Environment-compatible lightning protection for composites	3	2	X	X			Yes
Electromagnetic compatibility in fiber-composite aircraft	3	2	X	X			Yes
Develop automated aero-structural design system	2	2	X			No	Yes

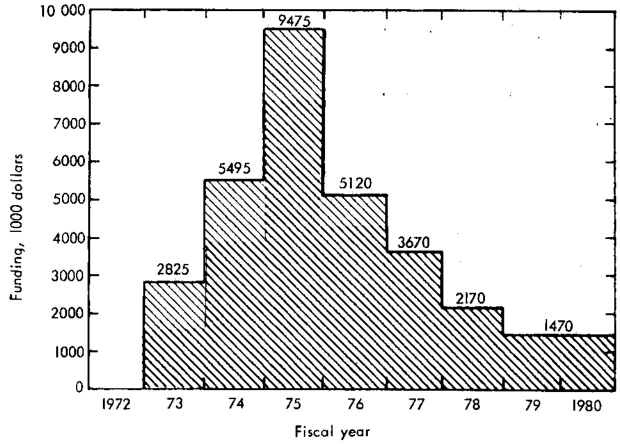

Figure 24. Funding summary - Structures and materials.

corresponding funding requirements are given in Table III and Figure 24, respectively. Detailed task descriptions, including funding and schedule requirements, are given in Sections 5.2.1 through 5.2.10.

5.2.1 Design, Build, and Test a Full-Size Section of a Typical Composite Wing Box

Area: Structures and Materials

Objective: (1) Demonstrate an all-composite, primary wing structure on a large commercial transport operating in a commercial environment. (2) Develop design requirements and manufacturing techniques and demonstrate structural integrity and useful service life for a large, advanced transport similar to the M = 0.95 study aircraft.

Scope: Two complementary programs will be conducted. A composite structure representative of an advanced transport will be designed into an L-100 center wing box, tested, and placed on an operational aircraft as quickly as possible to accumulate flight experience. The design and manufacturing concepts for a full-scale wing box representative of the M = 0.95 study aircraft will be developed, verified, and designed into a test article which will be fabricated for structural and environmental testing.

Approach: The program consists of two parts with several phases in each part as illustrated in Figure 25.

Part I: Accelerated Flight Demonstration Program

Phase I: Conduct a preliminary design study to select composite structural concepts representative of the M = 0.95 study aircraft which can be incorporated in the L-100 center wing box.

Phase II: Design an all-composite L-100 center wing box and conduct sufficient component tests to verify design concepts and details.

Phase III: Fabricate three test articles and a surface panel. One article will be used for static and environmental tests, one will be used for fatigue/exposure tests, and the other will be installed on an operational L-100 for flight service. A surface panel will be constructed as soon as possible and placed on a dummy box for accelerated environmental testing.

Part II: Full-Scale Composite Wing Structural Design R&D Program

Phase I: This phase provides the necessary engineering and manufacturing data base, including development tests, for proceeding into detail design of the wing box.

Phase II: Detailed design and analysis of the wing box will be performed, drawings will be released, and verification testing of selected critical component design details will be conducted. Quality assurance

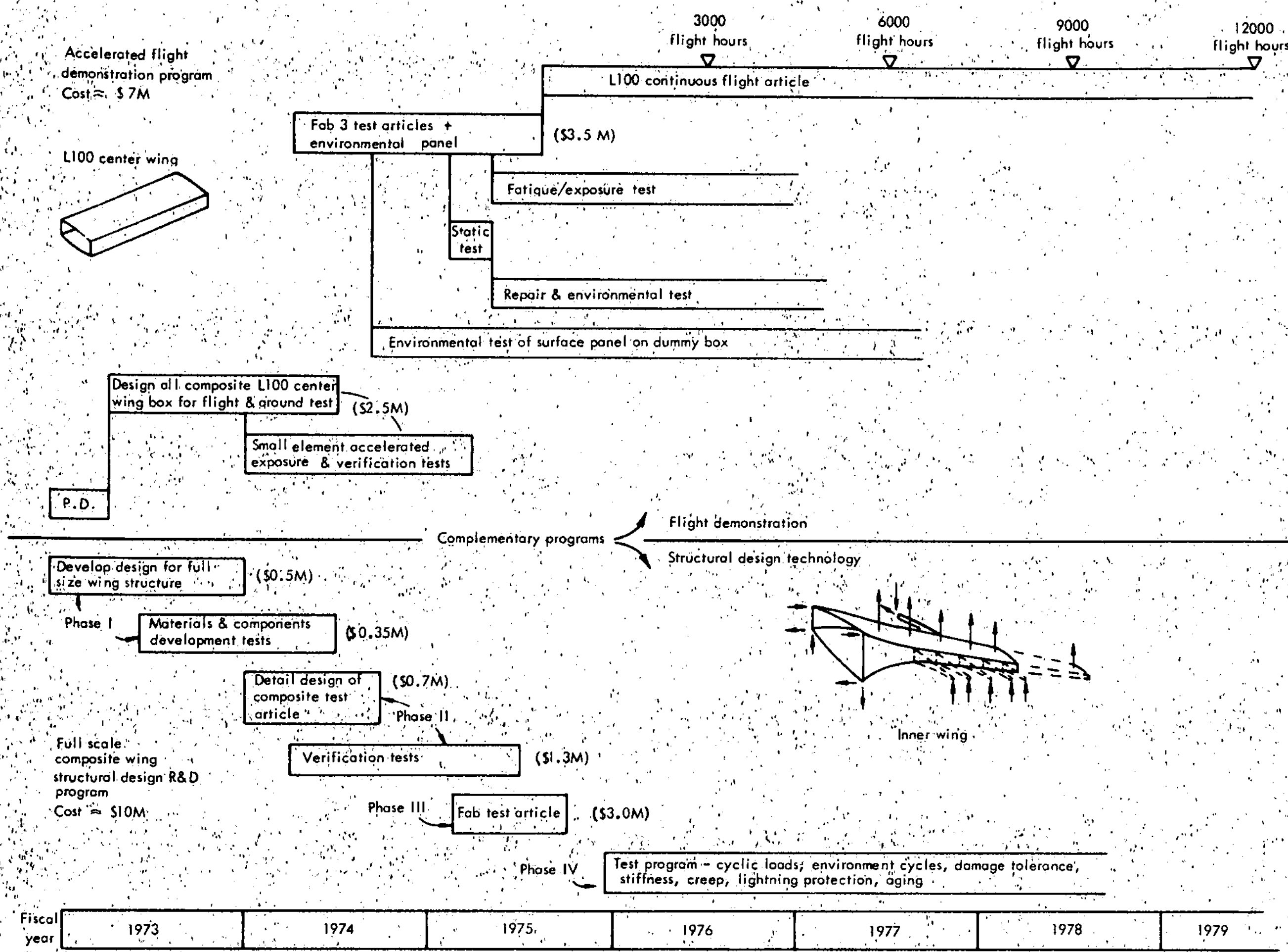

Figure 25. Program for accelerating the development of a M=0.95 aircraft wing box structure.

planning will be done during this phase for Phase III.

Phase III: This phase includes the development of manufacturing techniques and quality control procedures and the fabrication of a wing-box test article.

Phase IV: Laboratory testing will consist of creep, stiffness, fatigue, proof, environmental, and residual strength.

Results and Potential Benefits: The program will provide the necessary flight experience and confidence for applying composite materials to the primary structure of an advanced transport wing. Design details, manufacturing techniques, quality control procedures, weight, cost, and performance under simulated transport loads and environment will be provided.

Facilities: Use of an L-100 for installing composite wing and agreement with a commercial operator. Manufacturing facilities for large composite structures and structural test facilities for handling large components.

Funding Requirements: The funding requirements for Parts I and II of this task are shown in Figures 26 and 27, respectively. The additional cost for a second full-scale inner wing test article is estimated to be approximately $1,000,000.

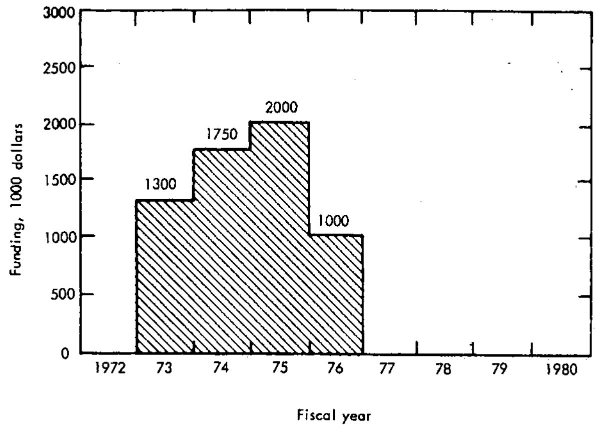

Figure 26. Funding required - Design, build, and test a full-size section of a typical composite wing box for a M = 0.95 airplane, part I.

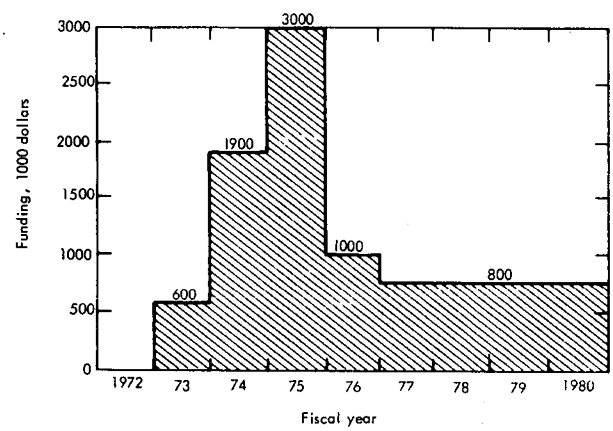

Figure 27. Funding required-Design, build and test a full size section of a typical composite wing box for a M = 0.95 airplane, part II.

5.2.2 Design, Build, And Test A Full-Size Barrel Section Of A Typical Composite Fuselage

Area: Structures and Materials

Objective: To develop the design, fabrication, quality control, and maintenance techniques necessary to produce a composite fuselage, and to demonstrate the weight reductions, structural integrity, and service life of a composite fuselage.

Scope: The program will consist of an in-depth design study to develop concepts for the fuselage which can be economically manufactured. A representative section of the fuselage will be designed in detail, followed by the fabrication of a test article for laboratory testing. The test article would be subjected to extensive laboratory testing to demonstrate fatigue endurance, resistance to lightning strike, aging, and other environmental conditions and to demonstrate maintenance and inspection procedures.

Approach: The fuselage section will be designed to the M = 0.95 structural design requirements and for the operating environment. The primary effort will be to develop structural concepts which can be adapted to low-cost tooling and manufacturing methods consistent with reliable structural integrity. Particular emphasis will be placed on the development of critical design details,

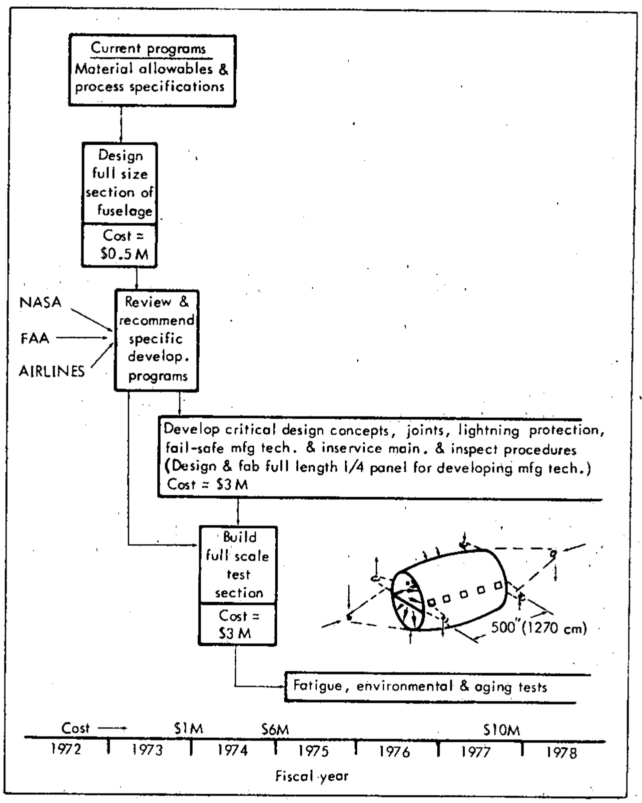

Figure 28. Development program for composite material fuselage of a M = 0.95 aircraft.

fail-safe concepts, lightning protection, and provisions for inservice maintenance and inspection. Figure 28 illustrates the ground test program for the composite fuselage.

Results and Potential Benefits: The program will demonstrate the benefits of advanced composite materials in a large transport, and promote the airline and public confidence necessary to gain acceptance of composites before committing to production.

Facilities: Existing fabrication facilities for large composite structures and structural test facilities for large components.

Funding: Funding requirements for this task are shown in Figure 29. The additional cost for fabrication of a second test article is estimated to be $750 000.

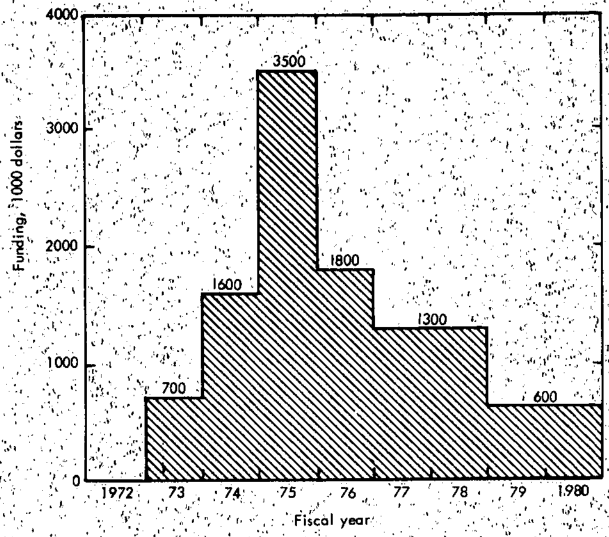

Figure 29. Funding required – Design, build, and test a full size barrel section of a typical fuselage for a M = 0.95 airplane.

5.2.3 Measurement Of Pressures On Oscillating Supercritical Wing Model

Area: Structures and Materials

Objective: To provide high-quality oscillatory pressure data for evaluation and modification of existing and new oscillatory aerodynamic methods.

Scope: This program will consist of the design, fabrication, and testing of a supercritical wing oscillatory-pressure model, and will include the initial development of the required instrumentation and model excitation systems.

Approach: A comprehensive study will be conducted to determine the best solutions to the known problems associated with this type of test, and to develop a detailed test plan consistent with the overall objectives of the program. Included in the first phase will be the development of an oscillatory-pressure measuring technique. It appears that the proposed tests can be successfully accomplished by means of the technique developed by Bergh in which the pressure orifices are connected through a "scanivalve" to a remote pressure transducer by tubes of known impedance characteristics. However, the limitations of this technique with respect to frequency of oscillation, required tube diameter and length, use of freon as a test medium, etc., must be carefully evaluated. Other matters which must receive careful consideration are the choice of model size and type, e.g., wall-mounted semi-span or sting-mounted full span, and the method of excitation. Methods of minimizing or accounting for model aeroelastic deflections must also be found.

The second phase will consist of the detail design and fabrication of the model, excitation system, and instrumentation system, and the installation and checkout of the complete system in the wind tunnel.

The third phase will consist of the testing. The model will be oscillated about an axis lying along the 35% chord line and in the plane of the wing. The tests will cover ranges of Mach number, reduced frequency, and static lift condition considered to be the most critical from a flutter standpoint.

Results and Potential Benefits: The oscillatory pressure data produced by this program will provide valuable insight into the presently unknown oscillatory aerodynamic characteristics of supercritical lifting surfaces. It will also provide a basis for the evaluation and empirical modification of both existing and future transonic oscillatory aerodynamic methods used for flutter and PSD gust analyses.

Facilities: Langley 16-ft (5.6 m) Transonic Dynamics Tunnel (freon).

Funding: Funding requirements for this task are shown in Figure 30.

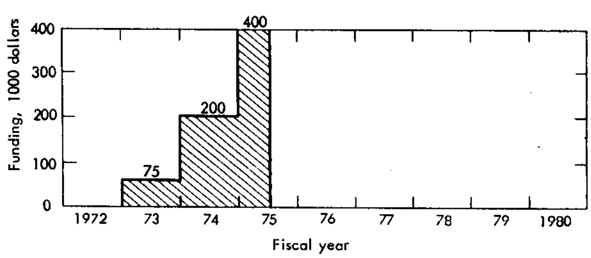

Figure 30. Funding required - Measurement of pressures on oscillating supercritical wing model.

5.2.4 Measurement Of Pressures On Oscillating Supercritical T-Tail Model

Area: Structures and Materials

Objective: To provide high-quality oscillatory pressure data for evaluation and modification of existing and new oscillatory aerodynamic methods.

Scope: This program will consist of the design, fabrication, and testing of a T-tail oscillatory-pressure model.

Approach: It is expected that the pressure measuring and model excitation systems developed for the wing tests described in Section 5.2.3 can, with reasonable modification, be used for these tests. Angular oscillation about the fin 35% chord line appears to be the most desirable initial mode of excitation. Otherwise, the approach on this program will be similar to that of the wing oscillatory pressure test program.

Results and Potential Benefits: Same as wing program except with respect to configuration.

Facilities: NASA Langley 16-ft (5.6 m) Transonic Dynamic Tunnel (freon).

Funding: Funding requirements for this task are shown in Figure 31.

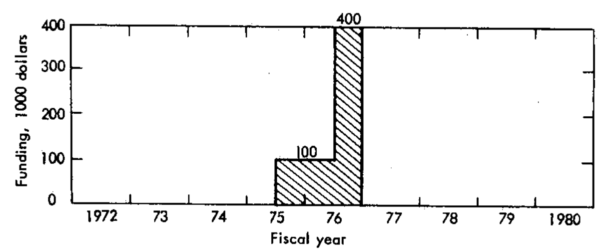

Figure 31. Funding required - Measurement of pressures on oscillating supercritical T-tail model.

5.2.5 Develop Adhesive Material for Structural Cold Bond

Area: Structures and Materials

Objective: Generate adhesive material and process for application and usage on structural joint application of transonic transport aircraft.

Scope: Develop, from actual design configuration joints, a material and process suitable for structural application.

Approach: A selection of typical structural joints in the wing and fuselage will be utilized for developing a system to bond assembly joints. This will be necessary for joining assemblies too large for autoclave bonding.

Results and Potential Benefits: Acquisition of design, weight, structural integrity, reliability, and maintainability data leading to airframe design commitment in 1980.

Facilities: Existing composite materials fabrication equipment suitable for large composite structural sections and assistance from adhesive manufacturing companies.

Funding: Funding requirements for this task are shown in Figure 32.

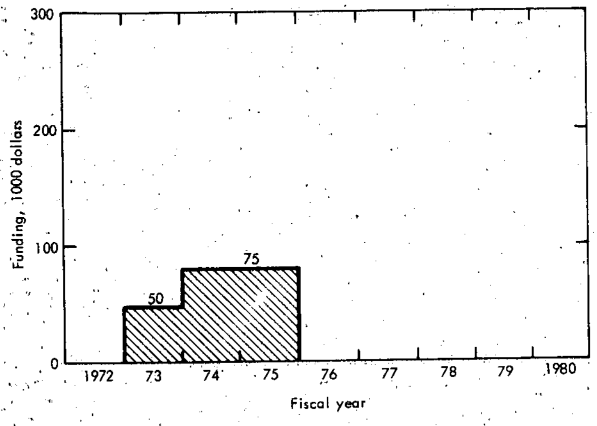

Figure 32. Funding required - Develop adhesive material for structural cold bond.

5.2.6 Lightning Versus Composites Overlaid On Metal

Area: Structures and Materials

Objective: The objective is to investigate basic lightning vulnerability of, and extant protection measures suitable for, the structural design of transport aircraft.

Scope: The study will be devoted to practical, near-state-of-the-art application/adaptation of composite skin interfacing with metallic underlying skin or rings, stiffeners, doublers, and gussets. The study will consider different composite-materials possibilities, lightning-effects/damage-types to be countered, and acceptable damage-protection measures.

Approach: When a literature search/analysis has progressed far enough to ensure that full advantage is being taken of other knowledge, lightning-test specimens will be fabricated from composite specimens. These will be examined for peripheral concerns such as electrical bonding, puncture voltage, and observable corrosion immunity. They will be lightning-tested for materials damage, sparking, and induced-voltage effects, as applicable. Proposed protective measures will be similarly tested and evaluated. Tentatively, these measures will include metallic coverings and diverter systems.

Results and Potential Benefits: The study will provide design data for both present aircraft modification and future vehicles. Currently, no usable data of this specific coverage exists. It will facilitate transition from all-metal aircraft to optimal construction with composites, and expand the background for optimization.

Faciliites: Facilities required include existing equipment, with instrumentation, for producing: controllable high-voltage impulses in the high-tens-of-thousands of volts; current transients with a rate of change approaching 10^{11} amperes/second; current transients of 200 000 amperes amplitude; charge transfer of up to 500 coulombs; and swept strikes.

Funding: Funding requirements for this task are shown in Figure 33.

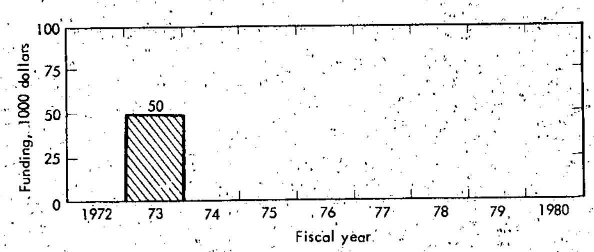

Figure 33. Funding required - Lightning versus composites overlaid on metal.

5.2.7 Lightning-Probability Modeling Of All-Composite Aircraft

Area: Structures and Materials

Objective: The objective of this task is to determine the areas of M = 0.95 transport aircraft likely to receive direct strikes by lightning and the proportion of strikes to each of these areas.

Scope: The study will determine long-spark attachment probabilities for the M = 0.95 aircraft with respect to physical configuration and, to the extent feasible to peculiar material characteristics.

Approach: Following a suitable literature search/analysis, initially nonconductive scale models of the airplane, or satisfactorily close approaches thereto, will be used as specimens. They will be variously coated to simulate (1) an airplane totally covered with continuous, lightning-protective metal, (2) an airplane with nonconductive skin but conductive items inside, (3) an airplane with semiconductive skin and conductive items inside, (4) an airplane like (2) but with metal leading- and trailing-edges, and (5) an airplane like (3) but with metal leading- and trailing-edges. The testing involves forcing a model to intercept a simulated lightning channel. A multiplicity of strikes is accomplished with the lightning channel at various angles with respect to the airplane in the pitch, roll, and yaw planes, simulating the approximate directional randomness of natural lightning. Photographs disclose the number of strikes, and hence the percentages, to various parts of the airplane.

Results and Potential Benefits: The study will contribute qualitatively to knowledge of potential direct-strike hazards to the airplane occupants and conductive hardware. The study will provide a quantitative baseline from which to make design-economics decisions (damage prevention versus repair) where safety is not at stake.

Facilities: Facilities required include existing long-spark electrical transient generators, with instrumentation (e.g., cameras).

Funding: Funding requirements for this task are shown in Figure 34.

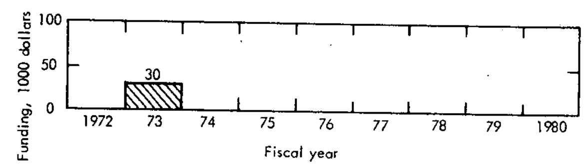

Figure 34. Funding required - Lightning probability modeling of all composites aircraft.

5.2.8 Environment-Compatible Lightning Protection For Composites

Area: Structures and Materials

Objective: The objective is to advance the state of the art in composite-aircraft lightning protection to obtain acceptable efficacy in other vital disciplines, e.g., electromagnetic compatibility, antennas, electrical grounding/bonding/shielding, electrostatic charging/sparking, corrosion, and erosion.

Scope: The study will be limited to seeking or defining a measure or system of measures for lightning protection that is consistent with other electronic/electrical/environmental mandates.

Approach: Basic physical parameters of applicable disciplines will be compared, by analysis and test, with those of various known or devised lightning-protection schemes. Conflicts will be studied. When a promising lightning-protection system is found, it will be analyzed in detail, though not to the exclusion of alternatives.

Results and Potential Benefits: A number of interacting, highly significant factors must be accommodated simultaneously. These include personnel, fuel, and electrical/electronic systems protection. They also include control of electrostatic charging/sparking, electromagnetic compatibility, antenna system performance, electrical bonding/grounding/shielding, corrosion, and erosion. A limited number of concepts now exist specifically for lightning protection of fiber-composite aircraft skin. For general application, however, there are drawbacks and/or unknowns that must be overcome, or at least determined. The intended result is the integration of known measures and/or the devising of new measures adequate to overcome the difficulties.

Facilities: Laboratories for experimental determination of lightning integrity, electromagnetic compatibility, and effects on antenna and radome systems are of central importance. Support is required in electrostatics, electric power-fault, manufacturing-research, structural-properties, chemical/metallurgical, and thermophysical-properties testing. All of the required facilities are currently available.

Funding: Funding requirements for this task are shown in Figure 35.

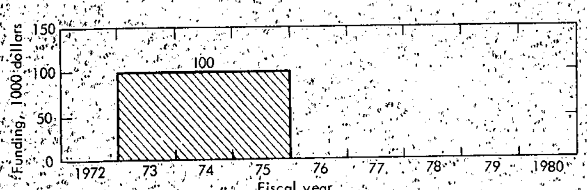

Figure 35: Funding required – Environment – compatible lightning protection for composites.

5.2.9 Electromagnetic Compatibility In Fiber-Composite Aircraft

Area: Structures and Materials

Objective: The objective is to devise a practical method of achieving electromagnetic compatibility in its broad sense in a basically all-composite aircraft.

Scope: An all-composite aircraft eliminates or profoundly alters the multi-faceted datum provided by an all-metal airplane and used heretofore in designing electrical and electronic systems and accomplishing electromagnetic compatibility. This task will consist of investigation of means, including "reduction to practice" where appropriate, to compensate for the change.

Approach: The study will examine in detail the constraints imposed on various interacting disciplines by the absence of the accustomed, massive, all-metal ground plane/enclosure or by the alteration from metal to semiconductor. To illustrate, one potential effect is the substantial alteration of antenna patterns. Another is inadequate personnel shielding from high-intensity electromagnetic radiation. Another is a high present potential for compromising fuel safety. Other typical concerns include electrical grounding/bonding/shielding, radio-frequency-interference coupling and energy generation, "rubbing noise," and the interplay of all these with corrosion and erosion. Means for offsetting the constraints will be considered, including such measures as changing intra-system interfacing philosophies. A constant premise will be that a solution to one vital problem that does not permit solutions to all the others becomes, at best, a waypoint toward the ultimate goal.

Results and Potential Benefits: This investigation is essential as a companion and follow-on to investigations for lightning protection. Its purpose is to avoid commitment to an airplane that cannot operate in the total operational environment.

Facilities: Laboratories for experimental determinations in electromagnetic compatibility, electrical grounding/bonding/shielding, electrostatics, antenna effects, and personnel hazards are the principal facilities required.

Funding: Funding requirements for this task are shown in Figure 36.

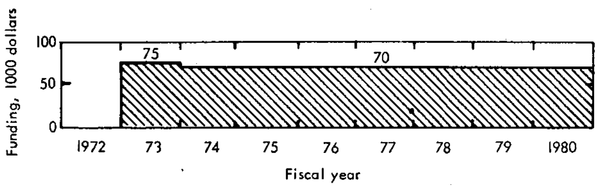

Figure 36. Funding required - Electromagnetic compatibility in fiber-composite aircraft.

5.2.10 Develop Automated Aero-Structural Design System

Area: Structures and Materials

Objective: To develop an integrated family of computer programs which will substantially increase the efficiency of structural analyses and result in final design loads earlier in the design cycle.

Scope: The prescribed system of programs will be sufficiently general to cover a wide range of airplane configurations, including all those variously proposed for transonic transport aircraft. The system will be organized in a form adaptable to the easy substitution of advanced methods as they become available, and to rapid turnaround following configuration changes.

Approach: Initial investigations will center around reviewing current systems, such as NASTRAN, to determine how these systems can be adapted to an automated system. Emphasis will be placed on establishing interface requirements between the various disciplines such as aerodynamics, weights, steady and dynamic loads, flutter, stress, etc. Both the content and form of interfacing data will be given major attention. Great emphasis will be placed on developing a system of programs which can be used efficiently throughout the design cycle. This will be accomplished by providing internal capability for the generation of basic aerodynamic and weights data as well as the flexibility required to enable ready insertion of data from external sources where they are available. The programs will initially be written for a UNIVAC 1106, or equivalent, computer. Adaptation to other computer systems will be carried out in subsequent programs.

Results and Potential Benefits: The results will consist of extensive program write-ups describing in detail all input requirements, assumptions, and other features. Fortran listings of all program modules will be provided along with input and output listings, program and input data decks, and a wide range of checkout cases.

Facilities: UNIVAC 1106 computer, or equivalent.

Funding: Funding requirements for this task are shown in Figure 37.

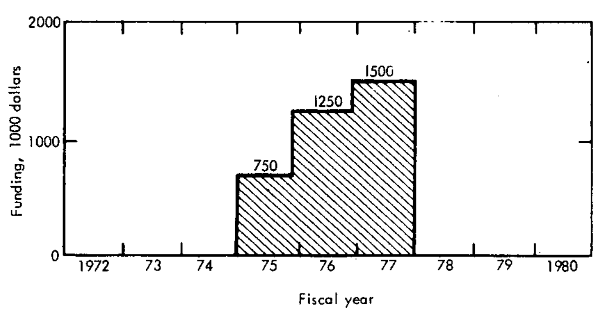

Figure 37. Funding required - Develop automated aero-structural design system.

6.0 POWER SYSTEMS

6.1 STATE OF THE ART

From a performance standpoint, propulsion systems have reached a fairly advanced state of readiness. The advent of severe noise and emission restrictions, however, has placed the utmost priority on technology improvement to maintain current performance standards. For the purposes of this discussion, it is assumed that technology items related to the powerplants are addressed by the engine contractors, while the installation and other propulsion-related system technology is the responsibility of the airframe contractors.

In propulsion installations, the challenge presented by transonic aircraft is the integration of the engine and airframe with a compatible, low-noise transonic nacelle-pylon arrangement. A major obstacle to the achievement of this goal is nacelle-airframe interference at transonic speeds. Although some wind-tunnel models with aft-mounted nacelle arrangements have exhibited drag rise delay up to near M = 1.0, the present upper limit for wing-mounted nacelles appears to be around M = 0.90. The suitability of wing-mounted nacelles for the larger transport aircraft emphasizes the importance of extending the design speed range for wing-mounted nacelle installations to higher Mach numbers. Internally, current state-of-the-art nacelles are close to optimum from the standpoint of minimum losses and compatibility. With the constraints of minimum nacelle frontal area for low drag, and long inlets and ducts for reduced noise, however, present day low-loss factors are virtually unattainable, and nacelle engine compatibility cannot be taken for granted. To assure that serious compatibility problems will not delay the development of future advanced-technology nacelle installations, engine-nacelle integration problems should be re-examined, considering new restrictions and requirements appropriate to the anticipated period of application.

The entire field of noise prediction and noise reduction must be advanced in order for transonic transport aircraft to become a reality without undue noise restriction and penalty. As defined in Volume I, certain state-of-the-art advances are assumed to be obtainable and are utilized in analysis of the study aircraft. These advances include a reduction in fan generated noise of 5 PNdB and a reduction in treatment weight and area of 20% for a given effectiveness. In order to achieve these advances, noise research and development programs must be initiated. Fortunately, many of the noise studies now in progress or planned for CTOL and STOL programs are applicable to the subject program. Current areas of investigation include quiet nacelles, jet noise, flap-impingement noise, and aircraft operational procedures.

Considerable work is now being performed in the area of quiet nacelles with single-stage fans. Additional programs must be initiated to optimize low-noise nacelles with 2-stage fans and to minimize turbine and combustion noise. Planned jet-noise programs appear to include sufficient depth to explore this area. If no improvements in jet noise are feasible by 1977, then consideration should be given to additional work. Planned blown-flap noise programs should be expanded to include transport aircraft operating and design parameters. Particular emphasis should be placed on takeoff operational techniques, since our studies indicate this to be the worst problem area relative to engine noise. Aircraft operational effects programs should be extended to include more complex maneuvers for noise reduction. In addition, the area of far-field aerodynamic noise has appeared as a potential noise limit for large transport aircraft. An investigation of this noise technology area is required as soon as possible.

6.2 R&D TASKS

Recommended R&D tasks in power systems and a summary of the corresponding funding requirements are given in Table IV and Figure 38, respectively. Detailed task descriptions, including funding and schedule requirements, are given in Sections 6.2.1 through 6.2.9.

TABLE IV. TASK SUMMARY - POWER SYSTEMS

Task	Readiness rating	Priority	Type			Retrofit	NASA support
			Study	Lab test	Flt test		
Nacelle-wing interference	3	1	X	X	X	No	Yes
Far-field aerodynamic noise evaluation	3	1	X		X	No	Yes
Aircraft operational techniques for noise alleviation	2	1	X		X	Yes	Yes
Blown flap noise evaluation	3	2	X	X		No	Yes
Redesign for FAR 36-15 EPNdB engine	2	2	X			No	Yes
Optimization of nacelle noise treatment	2	2	X	X		No	Yes
Engine-nacelle integration	2	2	X	X		No	Yes
Total airplane low-noise optimization	2	2	X			No	Yes
Unconventional approaches to noise reduction	3	3	X			No	Yes

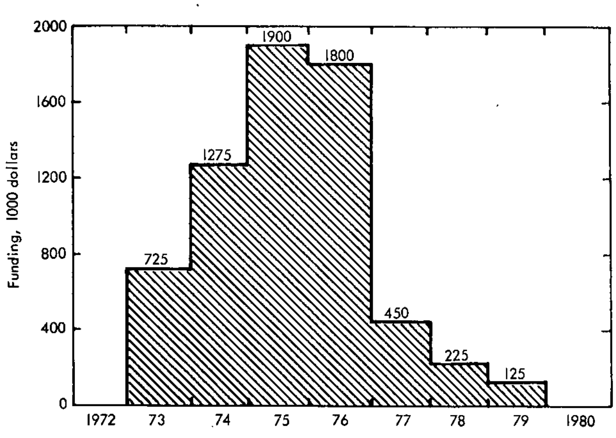

Figure 38. Funding summary - Power systems.

6.2.1 Nacelle-Wing Interference

Area: Power Systems

Objective: The object of this program is to develop a generalized empirical approach to the design of wing-mounted nacelle installations for airplanes which operate in the M = 0.90 to 1.0 range. The program will be designed to develop an understanding of nacelle position effects, variation of channel-flow distribution, and the influence of jet pressure.

Scope: This program is a long-range effort extending through 1979. It includes flow-through and powered-nacelle wind-tunnel model testing plus flight validation. Continued analytical studies will support the testing and provide redirection as indicated.

Approach: This program has already been initiated with the joint Lockheed-NASA M = 0.95 wind-tunnel model test. The test will be extended through several follow-on phases and the effects of nacelle position, along with variations in local channel-area distribution, will be generalized. A powered-nacelle test program will be planned and conducted using a larger scale, semispan version of a transport model. Several phases of this test may be necessary before power effects can be generalized. After considerable additional analysis, a flight-validation vehicle will be selected, a wing-mounted nacelle installation will be designed and built, and a flight-test program will be conducted. Flight validation is essential because it is impossible to simulate the complete interrelationships between nacelle, pylon, wing, jet, and streamtube without using a flight vehicle. Subsequent analyses will be aimed at correlation of the synthesized flow-through and powered-nacelle model test data with the flight-test results.

Results and Potential Benefits: Successful development of generalized procedures for integration of wing-mounted nacelles on transonic aircraft will remove a major obstacle to the achievement of efficient transonic cruise. Although wing-body combinations and transonic aircraft models with aft-mounted nacelles have operated with reasonably low drag up to M = 0.98, no data are available for wing-mounted nacelle installations. Lockheed system studies have indicated that serious c.g. location problems may be encountered by large aircraft with aft-mounted engines. Therefore solution of the problems associated with wing-mounted installations have become more compelling.

Facilities: A large, high-speed wind tunnel, such as the Cornell or NASA-Ames facilities, is required for the transonic model testing. The powered-nacelle portion of the testing will require a very-high-pressure air or nitrogen supply, on the order of 375 to 400 lb/in^2 (2.585 to 2.758 x 10^6 N/m^2). An experimental shop of adequate size to handle the aircraft chosen will be required.

Funding: Funding requirements for this task are shown in Figure 39.

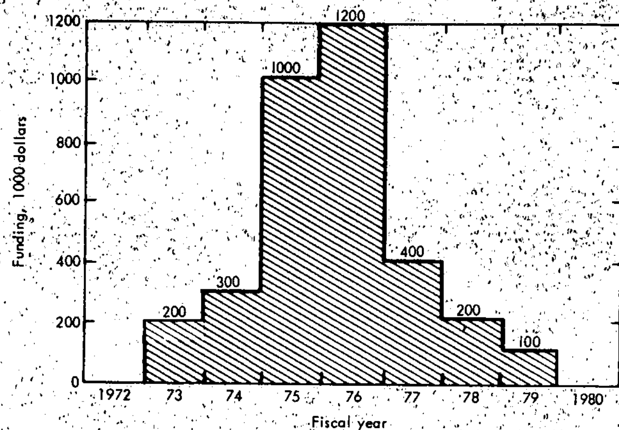

Figure 39. Funding required – Nacelle-wing interference.

6.2.2 Far-Field Aerodynamic Noise Evaluation

Area: Power Systems

Objective: The study will develop methods for evaluating far-field aerodynamic noise radiated from large aircraft.

Scope: This program will be an experimental and analytical effort. The experimental portion will be devoted to noise measurement of a large gliding airplane. The analytical portion will consist of the analysis of experimental data and independent theoretical work to formulate a noise evaluation and prediction methodology.

Approach: Noise measurement will be made of a gliding aircraft with a gross weight of 160 000 lb (72 546 kg) or greater. This will extend the current measured data bank to include aircraft approximately four times larger than any of those previously measured. Measurements will be taken for aircraft speeds up to 160 knots (82.2 m/s) with the aircraft aerodynamically clean, and with flaps and landing gear extended. Concurrent analytical work will be undertaken to interpret the test data and achieve a fuller understanding of this phenomena.

Results and Potential Benefits: Analytical procedures and low-noise design techniques will be evolved to accurately evaluate the radiated aerodynamic noise problem on large aircraft. The aerodynamic noise may impose a "floor" on noise reduction and the analysis may disclose noise minimization methods.

Facilities: A large very quiet airfield; an aircraft of approximately 160 000 lb (72 546 kg) or larger that is capable of an engine-off gliding approach and landing; and appropriate noise measuring instrumentation.

Funding: Funding requirements for this task are shown in Figure 40.

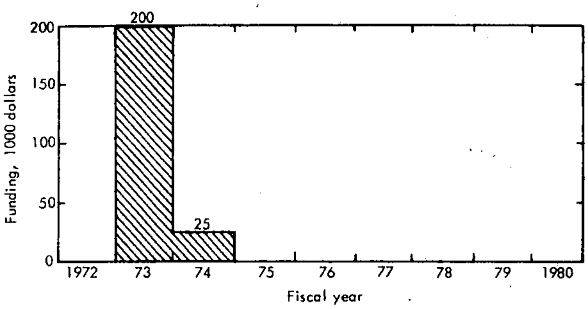

Figure 40. Funding required - Far-field aerodynamic noise evaluation.

6.2.3 Aircraft Operational Techniques For Noise Alleviation

Area: Power Systems

Objective: To extend the state of the art in aircraft operational noise alleviation.

Scope: A test program utilizing a very large aircraft.

Approach: Current test programs of this nature will be extended to include larger test vehicles. The applicability of multi-segment and high-angle approach, decelerating approach, automatic flap extension and retraction on take-off and landing, dispersed climbout paths, part-power takeoffs, etc., to very large aircraft will be evaluated. Noise measurements will be made under and to the side of flight paths. The procedures which show the most promise will be examined at operational airports on an experimental basis to determine the feasibility of such operations in real airport environments.

Results and Potential Benefits: Results will identify procedures which result in substantial noise reduction for larger airplanes and can be incorporated into real airport operation environments.

Facilities: Relatively isolated airport for the initial test program; a large jumbo-class airplane; specialized avionics on the ground and in the aircraft.

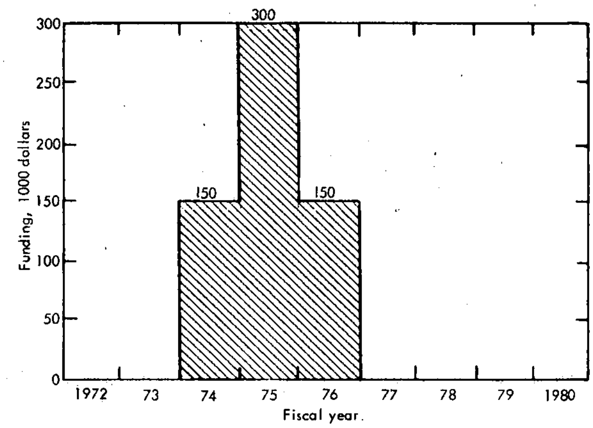

Figure 41. Funding required–Aircraft operational techniques for noise alleviation.

Funding: Funding requirements for this task are shown in Figure 41.

6.2.4 Blown-Flap Noise Evaluation

Area: Power Systems

Objective: To evaluate the phenomena of wing- and blown-flap noise amplification for transonic transport configurations.

Scope: This program is primarily an experimental investigation of wing- and blown-flap configurations as they affect the noise generation of a turbofan engine.

Approach: Existing STOL programs of a similar nature will be expanded to include appropriate nacelle-wing-flap configurations and fan and core engine jet velocities. Existing test facilities will be used with little modification. Emphasis will be on determining the effects of various wing-nacelle-flap geometries, including the effect of wing placement without flow impingement on the flaps.

Results and Potential Benefits: Program will provide analytical and design information for minimizing jet and jet-impingement noise as a function of basic geometry.

Facilities: Model engine and/or large-scale test facility suitable for noise measurements at various angles.

Funding: Funding requirements for this task are shown in Figure 42.

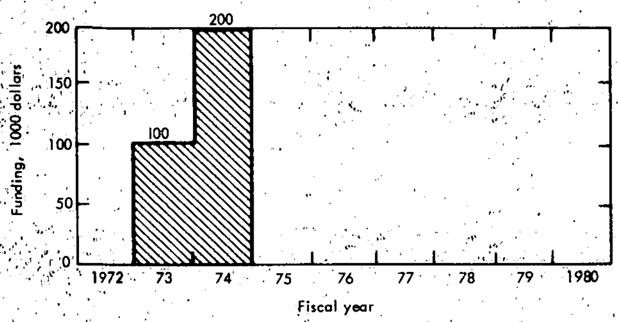

Figure 42. Funding required-Blown flap noise evaluation.

6.2.5 Redesign For The FAR 36 – 15 EPNdB Engine

Area: Power Systems

Objective: The objective of this study is to perform the design refinement phase of the subject study with an advanced (1985) powerplant. Phasing of the engine – airframe contractor schedules did not permit the accomplishment of this objective during the current study. Consequently, the Lockheed airplane which has been designed and analyzed combines a 1985 airframe with a 1980 engine and a nominal noise level of FAR 36 – 10.

Scope: The study will repeat portions of the last 3½ months of the current study with an advanced engine and a target noise level of FAR 36 – 15. All results affected by these changes will be re-evaluated. An addendum will be prepared to become a part of this final report.

Approach: A brief comparison of the P&W STF433 and GE No. 2 engines will be made initially to select the most suitable candidate. This will be followed by a complete design analysis of the resized airplane and the generation of a new performance data package. All disciplines, including economics, control of flight, and structures, will be re-exercised as required to produce a refined airplane design. In areas unaffected by the change in propulsion and noise requirements, no tasks will be repeated.

Results and Potential Benefits: The study will provide a consistent, advanced technology transport design for comparison with near-term configurations. Engine technology would be 1979, airframe technology 1980, and engine and aircraft certification date would be 1985. Performing this study would eliminate existing discrepancies in the program results.

Facilities: None.

Funding: The funding requirements for this task are shown in Figure 43.

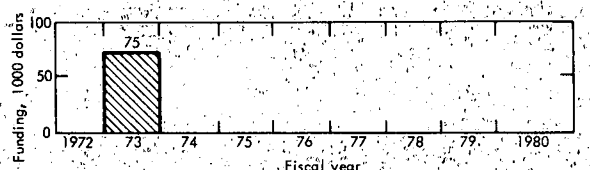

Figure 43. Funding required – Redesign for FAR 36-15 EPNdB engine.

6.2.6 Optimization Of Nacelle Noise Treatment

Area: Power Systems

Objective: To determine the optimum acoustical treatment for fan, compressor, and turbine ducts in terms of EPNdB reduction.

Scope: This is an analytical and experimental program aimed at design optimization of nacelle treatment. It will include analytical and design studies, laboratory test of duct treatment designs, and a real design for test on a full-scale engine. The fabrication and test of full-scale hardware, however, will be a part of an engine contractor program for development of a quiet, two-stage turbofan.

Approach: The emphasis will be on reduction of EPNdB for an airplane flyby. This requires an examination of noise reduction effects at all angles of noise radiation from fan and compressor inlets and discharge ducts, and turbine discharge ducts. One of the variables to be evaluated is double, triple, and quadruple tuning frequencies in different sections of duct. Continuing efforts will be made to find new concepts for treatment. The large number of variables for the optimization study will require extensive use of the digital computer. When the analytical phase is completed, laboratory tests will be used to validate the concepts. Upon completion of the laboratory test phase and consequent feedback into the analytical procedures, a full-scale nacelle treatment will be designed for evaluation on an engine test stand. The design will be for the 2-stage fan engine being developed in a parallel effort by an engine contractor.

Results and Potential Benefits: The results of this program will provide the analytical and design tools for determining the acoustic performance of an EPNdB optimized nacelle treatment, and the design of such a nacelle for evaluation on an engine test stand.

Facilities: Existing laboratory engine-duct acoustic test facilities.

Funding: Funding requirements for this task are shown in Figure 44.

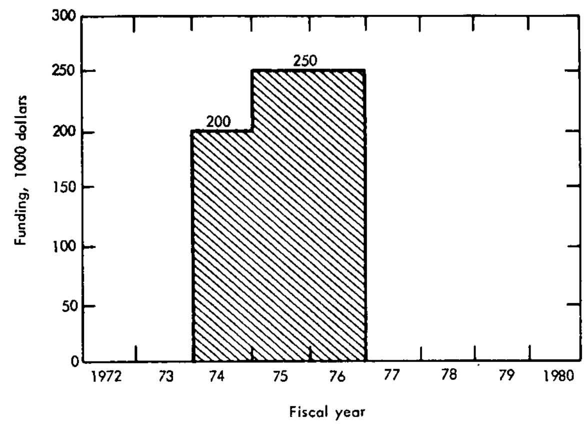

Figure 44. Funding required - Optimization of nacelle noise treatment.

6.2.7 Engine-Nacelle Integration

Area: Power Systems

Objective: This study will investigate the dual effects of low-noise and high-speed design requirements on internal nacelle aerodynamics and determine requirements for a compatible and efficient power package installation.

Scope: The study will investigate inlets, exhaust systems, and thrust reversers visualized for application to transonic transport aircraft. Auxiliary inlets and boundary-layer control devices will be studied. Splitters for inlet and exhaust-duct noise suppression will be evaluated. Methods for improving thrust-reverser performance and reducing cutoff speed will be investigated.

Approach: New concepts for inlets, exhaust systems, and thrust reversers will be proposed and developed analytically. Tests will be planned to fit the specific requirement of the concept and component under study. Small-scale static and wind-tunnel tests of inlet systems have limited value because of the large impact of scale effects. This type of testing will be performed at reasonably large scale. Exhaust systems can be successfully investigated at small scale, but care must be taken to simulate the internal response of the engine to nozzle mismatch and suppression effects. Isolated thrust-reverser performance can be studied with small, fairly simple test rigs. Interference effects, such as cross-ingestion and drag wipeout, however, require a fairly elaborate rig, such as a powered-nacelle semi-span model in a wind tunnel.

Results and Potential Benefits: The study will provide the trade-offs between noise, performance, and engine-nacelle compatibility required for the inception of a full-scale transonic transport program. Significant breakthroughs could result from the concentrated application of effort, particularly in the areas of noise treatment, nacelle integration, and thrust-reverser design.

Facilities: Inlet testing will require a large suction source, such as an exhaust blower or old engine, for simulation at an adequate scale. For basic nozzle and thrust-reverser testing, a pneumatics test lab with provisions for dual hot- and cold-flow nozzle testing will be necessary. A low-speed wind tunnel with high-pressure air supply will be needed for thrust-reverser interference tests using powered nacelles and a semi-span airplane model. All of these facilities are readily available.

Funding: Funding requirements for this task are shown in Figure 45.

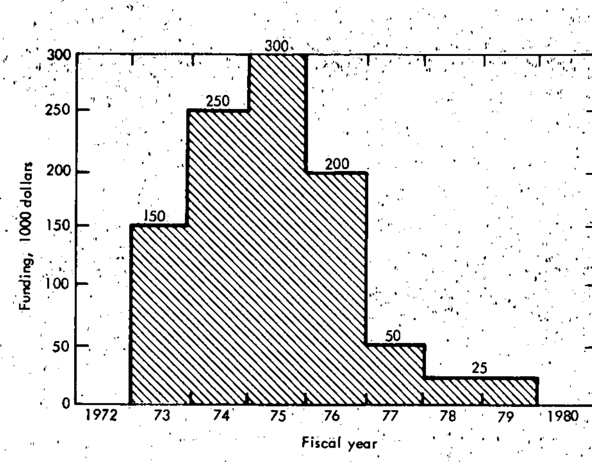

Figure 45. Funding required – Engine – nacelle integration.

6.2.8 Total Airplane Low-Noise Optimization

Area: Power Systems

Objective: To perform trade studies relating to aerodynamic characteristics, propulsion cycles, and noise treatment for the purpose of determining the optimum in each area for low-noise design of an airplane. From the trade studies, to formulate tools for the design of low-noise aircraft to minimize weight, performance loss, and cost.

Scope: This will be a trade study and design study program, oriented toward M = 0.95 to M = 1.2 transport aircraft.

Approach: Utilizing configurations derived from the current study contracts, further low-noise optimization trade studies of propulsion cycles, thrust requirements, acoustic treatment weight and losses, and wing area and high-lift devices will be conducted.

Results and Potential Benefits: A series of parametric trend curves will be generated to provide comprehensive design data for acoustic treatment.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 46.

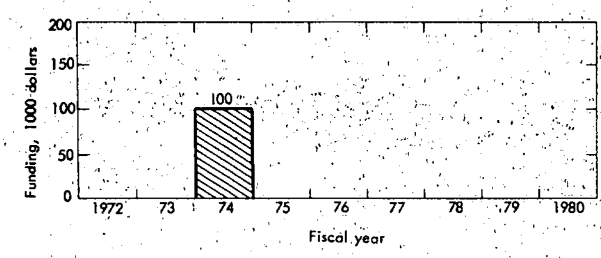

Figure 46. Funding required – Total airplane low-noise optimization.

6.2.9 Unconventional Approaches To Noise Reduction

Area: Power Systems

Objective: To investigate novel methods of noise alleviation with particular emphasis on buried engines or over-wing engines and slot-jet discharges along the upper wing and/or flap surfaces.

Scope: To investigate unconventional methods of aircraft noise reduction for transonic transport aircraft.

Approach: A thorough literature and industry search into the area of jet- and fan-noise reduction directed toward methods, procedures, and devices that have not been used previously in an aircraft context will be conducted. All possible methods, including ideas from other industries, will be evaluated. The feasibility of the various concepts and estimated benefits will be determined. A thorough study of buried engines and over-wing engines with slot-jet discharges will be completed.

Results and Potential Benefits: The most promising concepts will be applied to transonic transport configurations derived from the current contracts, when applicable, and to new configurations in cases such as over-wing mounted engines. Each new concept will be thoroughly evaluated relative to feasibility and expected noise reductions, weight and performance penalties, and possible problem areas. Recommendations will be made for further R&D efforts for promising applications.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 47.

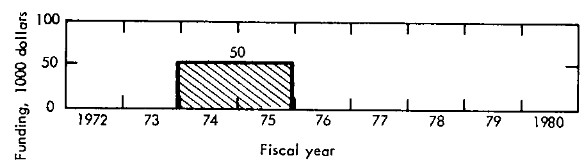

Figure 47. Funding required - Unconventional approaches to noise reduction.

7.0 CONTROL OF FLIGHT

7.1 STATE OF THE ART

The application of active-control technology permits the aircraft designer to achieve greater levels of performance while reducing weight and operating cost. One of the biggest payoff areas for active controls is in meeting handling-qualities requirements with airplanes lacking inherent stability. However, there is a requirement for design methods that are more suitable for use in preliminary design, where rapid trade-offs between active and passive stability are needed. A design method with considerable promise is model-referenced control-system optimization. A model-referenced flight-control system design process consists of an unaugmented aircraft, with its own natural dynamics, and a model which has suitable dynamics. The proposed task would develop the mathematical and computer methods to design an augmented aircraft with the characteristics of the model.

The study has also demonstrated that hardware problems exist. For example, one of the biggest obstacles to providing an accurate economic evaluation of roll-control system design, active flutter suppression, maneuver load alleviation and gust load alleviation is the lack of information on force- and moment-producing devices on supercritical airfoils. A task is proposed that would investigate various methods of achieving these forces and moments and provide the results in a format suitable for use in control-system design.

The application of redundant actuation systems to increase reliability establishes a requirement for actuator load balancing since the positioning of individual actuators differs slightly. Traditionally, this has been accomplished by designing compliance into the attaching structure and using close tolerances in the actuator/spool assemblies. This adds to the cost of the airplane. A different solution is proposed as a result of this study. Because the electro-hydraulic input servos are available for electrical compensation signals, the compliance is high and a hydraulic pressure feedback technique is devised to load balance the surface positioning servos by adjusting command signals to average out any tendency on the part of one actuator to counter the others. This method of force sharing is still in the preliminary design stage and requires a simulation study to prove the technical approach.

Modern electronic components have demonstrated a very high level of reliability in many systems, but not in others. Instead, the low system reliabilities have provoked adverse comments from operators, whose maintenance-hour/flight-hour ratio has increased. In such cases, it is usually not a question of losing the augmentation function but of the economics of maintenance. To prevent this occurrence in the use of fly-by-wire systems, design standards must be developed. NASA support is required to establish these standards, if costly industry duplication is to be avoided. In addition, standard and proven components of high reliability must be developed if the individual airplane development costs are to be minimized. The significant factor is that fly-by-wire systems have the potential to increase flight-control system reliability and reduce operating costs if the concept is properly developed.

The development of the Microwave Landing System must include the development of suitable aircraft antennas. Antenna modeling on scale-model aircraft for radiation-pattern studies will permit the development of candidate configurations that can be designed full-scale. Performance should be verified on full-scale aircraft. Since each airframe configuration has peculiar antenna radiation patterns, the appropriate airframe must be used to develop antennas suitable for that aircraft.

It is also important to consider man-machine interface problems. For example, there is considerable concern among pilots that the implementation of area navigation will cause an intolerable increase in cockpit workload, particularly in the terminal area. While area navigation, STAR, and SID routes will be highly standardized, and aircraft will automatically follow predesignated routes, in-flight changes in plan will occur and must be accomplished in a simple manner. These complex interactions among the pilots, aircraft, and the ATC system can best be studied using a functional real-time simulator that includes all significant elements of pilot work load.

An essential part of terminal-area air traffic control operations is to maintain a high traffic-acceptance rate during instrument flight conditions and under all probable wind variations. Development of the Microwave Landing System, full implementation of area navigation, and the up-grading of the VORTAC system are necessary improvements. Synthesis of these developments into a complete terminal-area system must be accomplished. Fast-time digital-computer simulation will allow a rapid exploration of the spread of environmental and aircraft characteristics as they affect terminal-area performance.

TABLE V. TASK SUMMARY - CONTROL OF FLIGHT

Task	Readiness rating	Priority	Type			Retrofit	NASA support
			Study	Lab test	Flt test		
Cockpit and control-display simulator and cockpit workload study	2	2	X	Simulation		No	Yes
Load balanced stabilizer actuation systems	2	2	X	X		No	Yes
Upgraded PFCS mean time between failure	3	2	X			No	Yes
Independent force and moment producing devices on supercritical airfoils	3	2	X	X		No	Yes
Terminal area simulation to maximize acceptance rate	2	2	X	Simulation		No	Yes
Aircraft handling qualities following multiple PFCS failures	2	2	X	Simulation		No	Yes
Development of MLS antennas	2	2	X	X	X	Yes	Yes
Model-referenced control system optimization	2	2	X	Simulation		No	Yes
Roll axis system monitoring	1	3	X			No	No

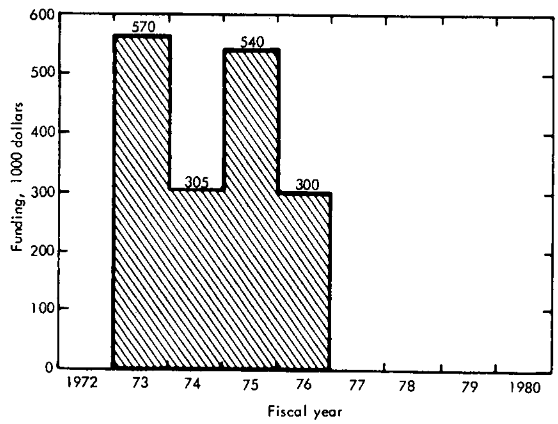

Figure 48. Funding summary -Control of flight.

7.2 R&D TASKS

Recommended R&D tasks relating to control of flight and a summary of the corresponding funding requirements are given in Table V and Figure 48, respectively. Detailed task descriptions, including funding and schedule requirements, are given in Sections 7.2.1 through 7.2.9.

7.2.1 Cockpit And Control-Display Simulator And Cockpit Workload Study

Area: Control of Flight

Objective: To develop a functional cockpit simulator to evaluate all significant elements of pilot work load for the 1980 time-period.

Scope: The simulator will be a two-man Captain/First-Officer arrangement with dual controls and instrumentation. It will be capable of fully-automatic flight over a pre-programmed route to touchdown, or can be flown manually with varying amounts of automaticity as desired.

Approach: Construct a functional cockpit simulator to reproduce "real-world" flight-deck activities in a transonic transport aircraft in the 1980 time frame. Based on an expected 1980 terminal-area configuration, conduct simulated approaches, departures, and go-arounds under a variety of operational situations. Using varying levels of cockpit automation, evaluate the several selected control/display layouts in relation to terminal-area flight effectiveness. Pilot task analyses will be used to evaluate cockpit workload. An Advisory Group will provide guidance during the course of the study. The group will include an airline pilot, a FAA air traffic controller, an engineering flight test pilot, and a human factors engineer.

Results and Potential Benefits: The study will develop the aspects of the cockpit configuration that optimize flight-crew performance, including overall layout, control/display layout and design, and operational procedure.

Facilities: Existing model shop, test laboratory equipment, and simulator housing.

Funding: Funding requirements for this task are shown in Figure 49.

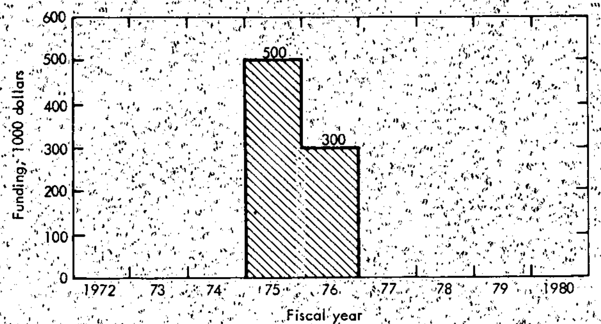

Figure 49. Funding required – Cockpit and control-display simulator and cockpit workload study.

7.2.2 Load Balanced Stabilizer Actuation Systems

Area: Control of Flight

Objective: This simulation effort will investigate the technical feasibility of the load-balancing concept for stabilizer actuation systems. In addition, gain and filter combinations will be synthesized for best compensation.

Scope: Simulation will include math-modeling of actuation system nonlinearities. Simulation will be accomplished on readily available analog computation equipment. Only differential pressure-compensation techniques will be evaluated.

Approach: A two-phase study will be performed. Phase one will be a short-term study to determine compensation feasibility. Phase two will be a parametric evaluation of the concepts limitations.

Results and Potential Benefits: The study results will confirm the capability of the load-balancing technique to compensate for PFCS tolerances. For each range of actuation variables, a set of compensation gains and filter combinations will be derived. The study will aid in the development of future control-system designs where load-balancing may be a problem.

Facilities: Simulator laboratory, currently in operation.

Funding: Funding requirements for this task are shown in Figure 50.

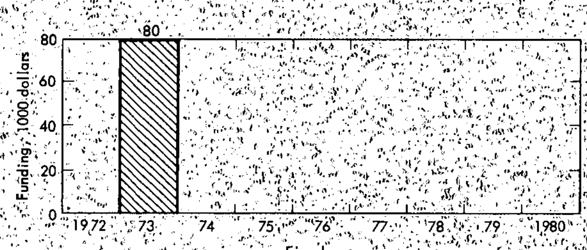

Figure 50. Funding required – Load balanced stabilizer actuation system.

7.2.3 Upgraded PFCS Mean Time Between Failure

Area: Control of Flight

Objective: The objective of these studies is the reduction of maintenance actions for support of the electronic flight-control system.

Scope: The study will be limited to an investigation of primary flight-control system reliability for transonic transport aircraft and the impact of channel simplicity and environmental stress protection on improving reliability.

Approach: On the basis of the experience gained in design of sophisticated augmentation systems for transport aircraft, guides for minimization of part count on the building-block circuit level will be drafted. In addition, new packaging concepts and ambient environmental-control concepts will be examined. The relationships between environmental stress protection and improved reliability will be investigated.

Results and Potential Benefits: The study will provide design guides. Comparative data with state-of-the-art augmentation systems will be established. Projected system MTBF improvement will be established.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 51.

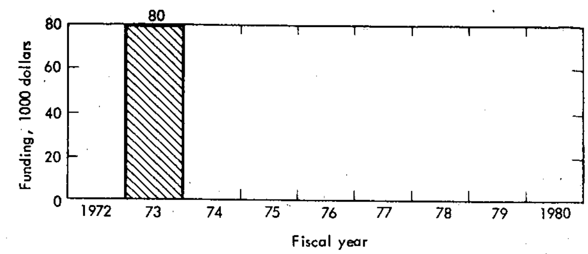

Figure 51. Funding required – Upgrade PFCS mean time between failure.

7.2.4 Independent Force- And Moment-Producing Devices On Supercritical Airfoils

Area: Control of Flight

Objective: To provide flight-control information for the design and evaluation of active flutter suppression, maneuver load alleviation, and gust load alleviation systems. The information is also required for roll-control system design when the design incorporates very flexible wings.

Scope: The study will include analytical and wind-tunnel work on a variety of supercritical wing control devices.

Approach: Analytical studies will be initiated to determine the most promising devices for wind-tunnel evaluation. Moment-producing devices will receive special consideration. Time lags, hinge moments, and drag will be studied.

Results and Potential Benefits: The risk levels in designing active structural-control systems will be greatly reduced and more accurate economic assessment of possible benefits will be possible.

Facilities: Existing digital computer and transonic wind tunnel.

Funding: Funding requirements for this task are shown in Figure 52.

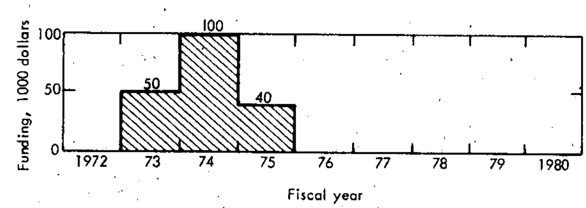

Figure 52. Funding required – Independent force and moment producing devices on supercritical airfoils.

7.2.5 Terminal Area Simulation To Maximize Acceptance Rate

Area: Control of Flight

Objective: The objective of this study is to determine methods for achieving a runway acceptance rate of the order of 60 aircraft per hour to a touchdown timing tolerance of 5 seconds, one sigma, or better. The study is compatible with Recommendation 2 in Reference 3.

Scope: The terminal area simulated will include several predefined arrival routes (STARS), a spread of vertical approach angles responsive to noise abatement procedures, and time-progress control along the STARS. The effects of winds and wind variability will be investigated. The probable spread of aircraft performance characteristics will be included.

Approach: Digital-computer simulation will be used to study the spectrum of parameter variations. Pilot dynamics will be included in the control loop so that the results will be valid for manual flight control. The wind effects will recognize the existence of the real-time wind vector in the ARINC Mark 2 Area Nav Computer and the existence of the ARINC VHF data link capable of transmitting such data to the ground environment. Fast-time simulation will be used. Visual plotters will be used as readouts.

Results and Potential Benefits: The study will permit maximization of terminal-area and runway-operations rate consistent with safety and ground noise-level constraints.

Facilities: Existing digital computer and peripheral devices.

Funding: Funding requirements for this task are shown in Figure 53.

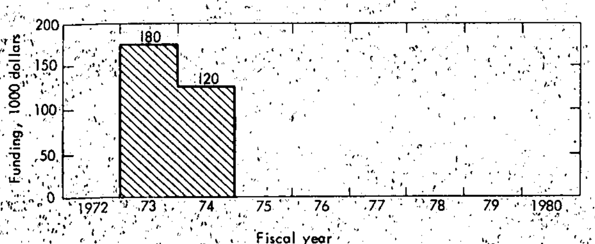

Figure 53. Funding required – Terminal area simulation to maximize acceptance rate.

7.2.6 Aircraft Handling Qualities Following Multiple PFCS Failures

Area: Control of Flight

Objective: The program will provide pilot assessment of handling qualities following failures in the PFCS and interfacing systems.

Scope: Aircraft simulation will be limited to the baseline M = 0.95 configuration, using the best available aero data. Cockpit environment will be typical for a large transport, with realistic exterior visual cues.

Approach: The simulation set-up being used at present to determine augmentation requirements for the aircraft will be used for this study. Pilots will fly the simulator, experience multiple PFCS failures and record resulting handling characteristics using Cooper rating scales.

Results and Potential Benefits: Results of the study will confirm PFCS design integrity in the event of multiple system failures. The simulation will also provide a starting point from which PFCS caution and warning criteria and control-panel design can be derived.

Facilities: Simulator laboratory, currently in operation.

Funding: Funding requirements for this task are shown in Figure 54.

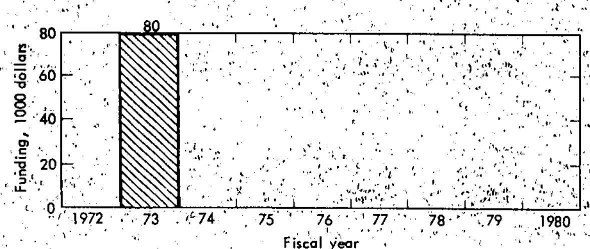

Figure 54. Funding required – Aircraft handling qualities following multiple PFCS failures.

7.2.7 Development Of MLS Antenna System

Area: Control of Flight

Objective: The study will develop a MLS antenna system for the M = 0.95 airplane for terminal-area operations.

Scope: The development of suitable MLS antennas will be accomplished through antenna modelling techniques for feasibility demonstration.

Approach: Laboratory model antennas will be designed and developed for feasibility demonstration. Radiation-pattern studies will be conducted to determine satisfactory coverage for both C-band and Ku-band components. Scale-model techniques will be used for measurements of the C-band antenna to examine the omnidirectional pattern characteristics. A full-scale sectional mockup will be required for the Ku-band studies. Antennas will be modelled, tested, and reconfigured as required to secure the proper spatial coverage. The full-scale preliminary designs of the selected antennas will be made from which final designs can be derived.

Results and Potential Benefits: The study will provide the basis for the detailed design of antennas suitable for the LGS function.

Facilities: Existing antenna laboratory, including antenna pattern measuring range, and model shop.

Funding: Funding requirements for this task are shown in Figure 55.

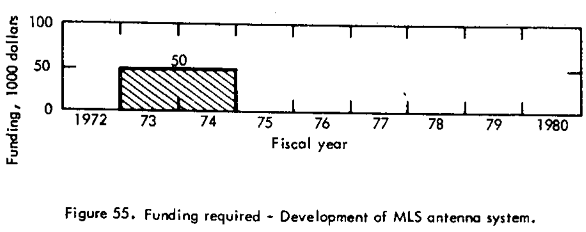

Figure 55. Funding required - Development of MLS antenna system.

7.2.8 Model-Referenced Control System Optimization

Area: Control of Flight

Objective: The study will develop techniques which will provide optimum control-surface sizing in the preliminary design phase.

Scope: The study will be limited to developing new control-system techniques and applying them to the M = 0.95 configuration to investigate a further reduction in control surface sizing.

Approach: The conventional techniques (such as root locus, Nyquist, Bode and Nicols) are good for designing control systems with single inputs and single outputs. An aircraft, however, is a system with multiple inputs (three or more pilot controls) and multiple outputs. Modern control technology, using model-following and model-referenced techniques, provides a solution to this problem. The approach suggested for this task consists of:

(1) Finding mathematical models that have good transport handling qualities for both lateral-directional and longitudinal modes.

(2) Determining the best computer optimization techniques to specify the feedback gains and control surface sizes for the subject aircraft.

(3) Developing an orderly design iteration process for implementing the procedure.

Results and Potential Benefits: The procedure proposed here provides a quantitative method of trading off active and passive stability which is essential to an effective preliminary design effort. The use of direct-lift and side-force control devices is enhanced. Further reductions in aircraft weight are possible.

Facilities: Existing digital computer.

Funding: Funding requirements for this task are shown in Figure 56.

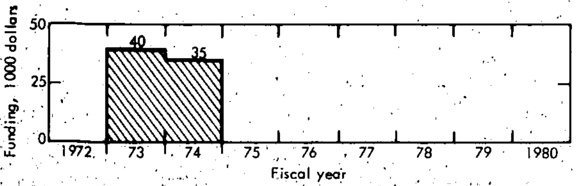

Figure 56. Funding required - Model - referenced control system optimization.

7.2.9 Roll Axis System Monitoring

Area: Control of Flight

Objective: To derive an efficient means for monitoring the multiple actuation systems on the roll axis of the M = 0.95 study airplane. The amount of circuitry added to accomplish the monitoring will be minimized.

Scope: The study will be limited to the basic roll-axis driving mechanisms configured for the baseline configuration.

Approach: The study will consider alternative approaches to the monitoring task, such as new logic statements which require fewer comparators and techniques other than comparison monitoring.

Results and Potential Benefits: By reducing the circuitry required to monitor the roll-axis PFCS, overall system MTBF is improved, and system weight and complexity are reduced.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 57.

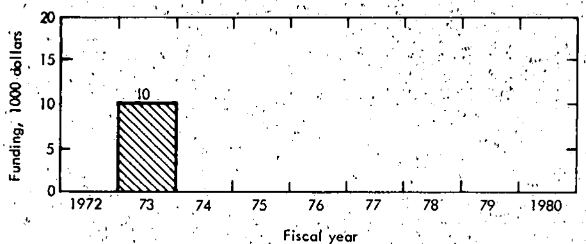

Figure 57. Funding required - Roll axis system monitoring.

8.0 ECONOMICS

8.1 STATE OF THE ART

The two major types of cost within any industry are investment cost and operational cost. In many instances, within the airline industry, total investment cost is extremely difficult to identify. In addition, complete quantitative awareness of total operational cost and its distribution is not prevalent. Since these costs are instrumental in determining return on investment, it is necessary that they be identified and minimized if an optimized return is to be realized.

Present total system investment methods of cost determination used within the aerospace industry do not reflect realistic values. Many airlines feel that certain investment costs are not being properly considered in terminal facilities, ground support facilities, service/support equipment, and other aspects of overall start-up costs. It is unlikely that operating costs are either identifiable or controlled to the extent required for efficiency of operation. Indirect operating cost continues to grow as a percentage of total operating cost. Advanced technology aircraft are in production, with extensive technological advancements being planned for the coming generations of aircraft. Current ground operations and equipment are not compatible with these aircraft, nor is full advantage being taken of the benefits that can be derived from the application of advanced technology in the ground operations area. Research and development studies to identify and categorize each cost associated with air transportation system operation, and define the application of advanced technology throughout the system, will be highly beneficial to the airline industry and, hence, the general public.

In order to accomplish this, separate studies are required for updating direct and indirect costing methods. Presently, direct operating costs are based on 1967 ATA standards. Although these standards have been modified to some extent for current usage, they do not include the total effects of advanced technology in materials, systems, air and ground equipment, and operational techniques. Lack of uniformity is in greater evidence in indirect operating cost determination. Several different methods are available, but none has been officially sanctioned by the airlines or other related agencies. Because of these deficiencies, resulting return-on-investment values are inaccurate on an absolute scale. Concerted efforts should be undertaken to develop methods for producing accurate direct and indirect operating costs and relating these costs on a current/advanced-technology basis.

8.2 R&D TASKS

Recommended R&D tasks in economics and a summary of the corresponding funding requirements are given in Table VI and Figure 58, respectively. Detailed task descriptions, including funding and schedule requirements are given in Sections 8.2.1 and 8.2.2.

TABLE VI. TASK SUMMARY - ECONOMICS

Task	Readiness rating	Priority	Type: Study	Type: Lab test	Type: Flt test	Retrofit	NASA support
Advanced technology application-ground investment	2	2	X			No	Yes
Update of direct and indirect costing methods	2	2	X			No	Yes

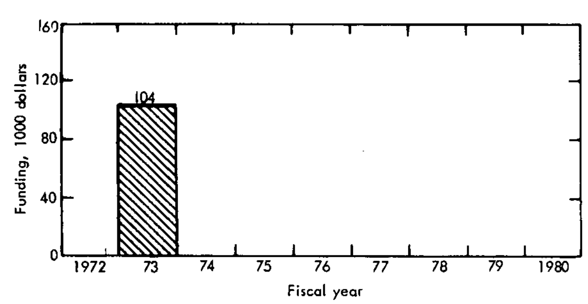

Figure 58. Funding summary - Economics.

8.2.1 Advanced Technology Application-Ground Investment

Area: Economics

Objective: To determine the levels of advanced technology that can be applied within the ground element of the air transportation system, the requirements for compatibility with advanced technology airplanes, costs involved, a time-phased implementation schedule, and the benefits that will be derived in an operational environemnt with current and advanced technology aircraft.

Scope: The status and availability of pertinent advanced technology will be established and its applicability determined relative to:

(1) Current and advanced technology aircraft.

(2) Air terminal system operations.

(3) Ground facilities and equipment.

(4) Terminal area airplane operations and communications.

(5) Crew training.

(6) Maintenance of advanced materials and systems.

(7) Aircraft service and support.

A cost and benefit analysis, with improvements in the quantification of these benefits, will enhance the credibility and acceptance of study results by potential users.

Results and Potential Benefits: The study will provide an advanced technology system definition relative to air terminal operations, ground equipment, and facilities. Economic analyses of conventional versus advanced systems will establish a priority system. Bases for decisions will be presented in the form of initial investment, operating costs, and benefits derived from an optimized system.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 59.

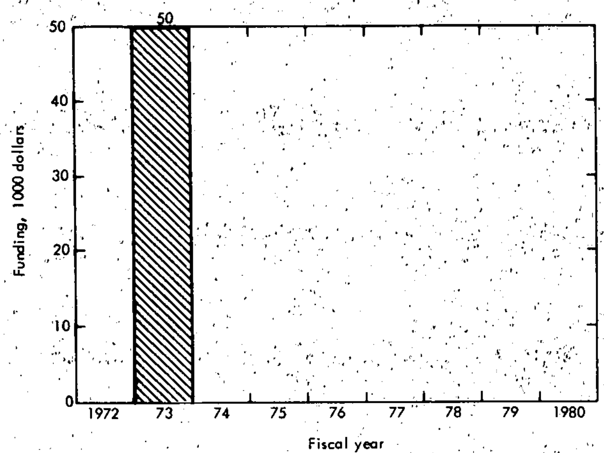

Figure 59. Funding required - Advanced technology application - ground investment.

8.2.2 Update Of Direct And Indirect Costing Methods

Area: Economics

Objective: To update direct and indirect operating costing methods so that the effects of advancements in materials, systems, and other technologies will be included. A method for DOC and IOC calculations which is acceptable to the aerospace industry and related organizations will be a study objective.

Scope: The study will include revisions to the 1967 ATA Standards for Direct Operating Cost and to a compilation of proposed methods for estimating airline indirect operating cost.

Approach: The results of previous efforts will be utilized in estimating direct and indirect costs. Coordination with appropriate associations, agencies, and industries will be established and maintained in order to formulate acceptable criteria for costing methods. Validation will be through comparative analyses of actual direct and indirect operating costs under known conditions.

Results and Potential Benefits: The study will provide an accurate method for estimating direct and indirect operating costs for airline operation, expansion, or new equipment acquisition. It will provide a dependable means for pre-determining these costs in order to properly assess the total investment required for a desired return on this investment. Improvements will result in the quantification of benefits derived from the application of advanced technology.

Facilities: None.

Funding: Funding requirements for this task are shown in Figure 60.

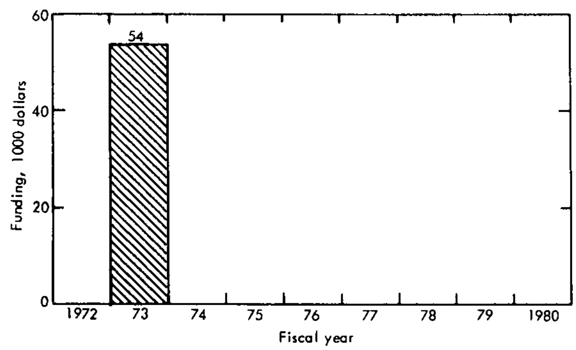

Figure 60. Funding required – Update of direct and indirect costing methods.

9.0 R&D PROGRAM PLAN

The research and development requirements discussed in this section are a summary of the tasks outlined in Sections 3.0 through 8.0. The most urgently required tasks are listed in order of priority in Table VII. The last item on the list, denoted by the asterisk, does not meet the criteria of Priority 1, but is listed because of its importance in determining guidelines for future flight demonstration vehicles.

The order of importance of the R&D tasks of Table VII corresponds to the technology benefits outlined in Phase II, Section 7.0 of Volume I. Advanced materials are shown to have the highest priority in tasks (1) and (2). Supercritical wing technology ranks next in priority with tasks (3) and (6). Although not in the category of benefits, but rather as design constraints, the tasks associated with noise reduction are denoted by items (4), (5), and (7). The emphasis placed on these tasks is a result of both the anticipated technology benefits and the correction of deficiencies in technology readiness. This accounts for the high priority given to advanced materials.

Significant benefits are realized through the application of all of the technologies represented in this table. Technology deficiencies have been identified for large structures containing a high utilization of advanced composite materials, the interference of wing-mounted nacelles and pylons with supercritical wings, and transonic aircraft design methodology. The large emphasis on the achievement of noise levels 10 and 20 EPNdB below FAR 36 criteria has identified requirements for R&D programs in the prediction of the far-field aerodynamic noise of advanced transport configurations, in the achievement of lightweight acoustically treated engine nacelles, and in the validation of noise alleviation through flight operational techniques.

TABLE VII. PROGRAM REQUIREMENTS

Program priority	Task section number	Task
1	5.2.1	Design, build, & test full-size section of typical composite wing box
2	5.2.2	Design, build, & test full-size barrel section of typical composite fuselage
3	6.2.1	Nacelle-wing interference.
4	6.2.2	Far-field aerodynamic noise evaluation
5	3.1.1	Design, build, and test a lightweight acoustically treated nacelle
6	4.2.1	Transonic design and analysis methods
7	6.2.3	Aircraft operational techniques for noise alleviation
*	3.2.2	Cost benefit study of size effects for a flight demonstration vehicle

TABLE VIII. PROGRAM COSTS IN MILLIONS OF DOLLARS FOR FIRST PRIORITY TASKS

Task \ FY	1973	1974	1975	1976	1977	1978	1979	1980	Total	Technology category
1. Composite wing box	0.600	1.900	3.000	1.000	0.800	0.800	0.800	0.800	9.700	Materials
2. Composite fuselage section	0.700	1.600	3.500	1.800	1.300	1.300	0.600	0.600	11.400	Materials
3. Nacelle-wing interference	0.200	0.300	1.000	1.200	0.400	0.200	0.100		3.400	Supercritical
4. Far-field noise	0.200	0.025							0.225	Noise
5. Lightweight acoustic nacelle	0.340	0.660	1.000	1.500	2.500	1.500			7.500	Noise
6. Transonic design and methods	0.500	0.600	0.700	0.800	0.800	0.600	0.500		4.500	Supercritical
7. Operational techniques--noise		0.150	0.300	0.150					0.600	Noise
* Cost benefit size effects	0.175								0.175	Systems
Total	2.715	5.235	9.500	6.450	5.800	4.400	2.000	1.400	37.500	

Costs and schedules for the first-priority tasks are given in Table VIII and Figure 61, respectively. It should be noted that five of these efforts involve flight programs. The top-priority composite-wing-box effort is an accelerated development program with the objective of accumulating flight hours at a high rate on a flight test article. It is proposed that this be accomplished with a cargo transport operated by a commercial airline. It is thus projected that flights would begin in FY 75. Six thousand flight hours would be accrued by mid FY 77 and 12 000 hours by mid FY 79. This program can provide valuable data on the maintainability of composite structures in an airline environment with the attendant exposure to the elements. A program of this type also

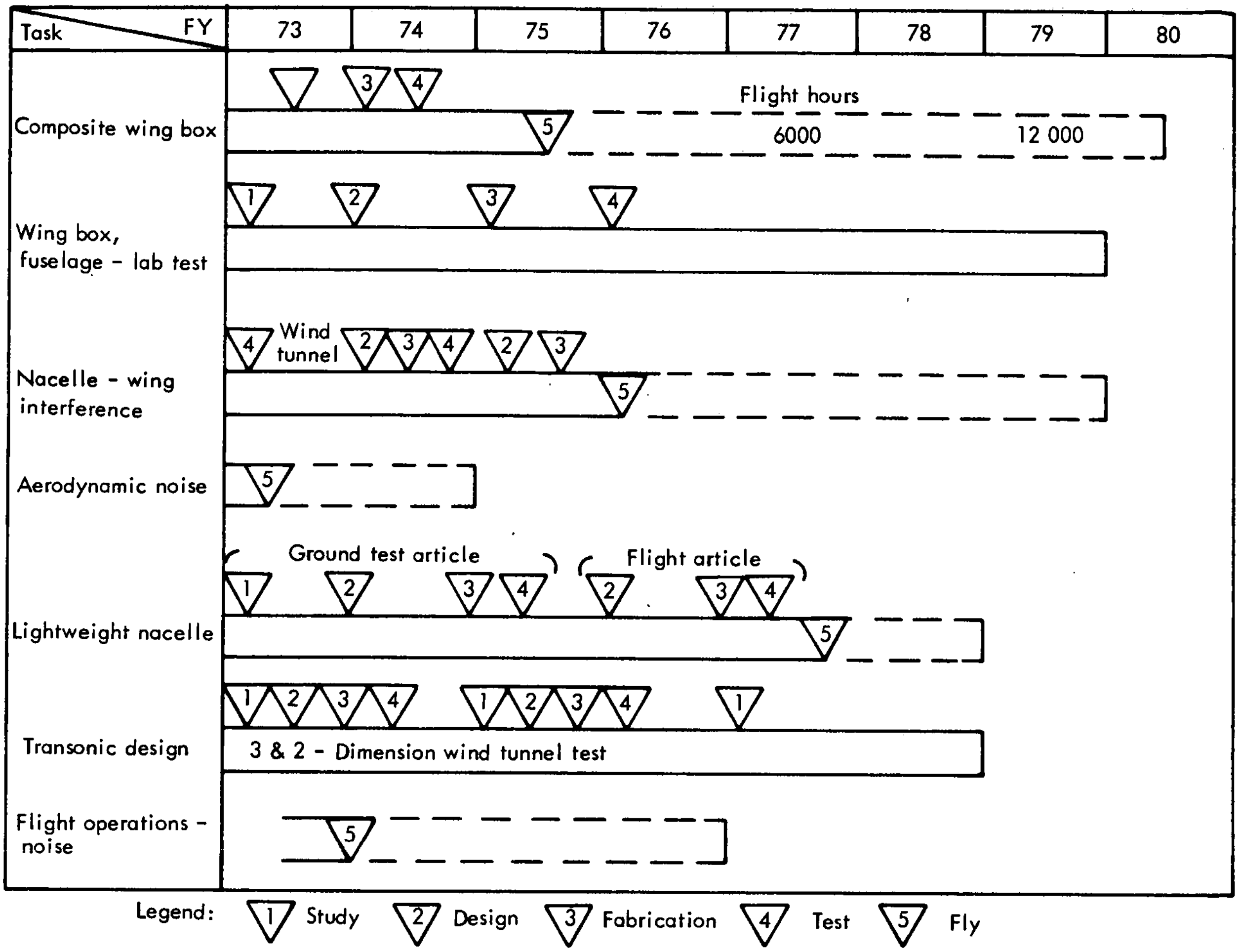

Figure 61. Schedule for first priority tasks.

provides the experience and confidence necessary for eventual acceptance of composite material structures.

The laboratory test program for large-scale wing-box and fuselage sections is essentially a structures technology program with the testing continuing from FY 76 through FY 79. These test programs include cyclic loads, environmental cycles, damage tolerance, stiffness, creep, lightning protection, and aging.

The nacelle-wing integration effort begins with the second generation wind-tunnel testing of the Lockheed M = 0.95 model. This is followed by design, fabrication, and testing of refined nacelle-pylon configurations and flight tests of the final configuration.

The aerodynamic noise flight test program can begin as soon as the flight operational techniques have been developed.

The lightweight, acoustically treated nacelle effort evolves through design, fabrication and laboratory testing of both ground- and flight-weight test articles prior to flight tests in late FY 77.

The transonic design and analysis methodology effort involves two- and three-dimensional wind-tunnel tests followed by evaluation of data and refinement of methodology in an iterative fashion.

The effort on aircraft operational techniques for noise alleviation by means of steep flight paths, automatic flap extension, and other appropriate operations is postulated as a more detailed extension of current programs to include larger test vehicles. As with the aerodynamic noise effort, this program can begin relatively soon, depending only upon the development of flight operational procedures.

Including the seven first-priority tasks, a total of 49 R&D tasks were identified as a result of the study. The total program costs are outlined in Table IX and are shown graphically in Figure 62. In these illustrations, the research and development tasks are divided into five technology categories. A new technology category of Systems Studies represents the areas associated with system integration and include design, economic studies, and systems analysis efforts. Some system study efforts cross the lines of several technology areas. The total cost of all programs shown is $80.405 million. Of this total cost, advanced materials account for $31.715 million or 39.4%, systems studies account for $24.490 million or 30.5%, noise reduction accounts for $11.260 million or 14.0%, and supercritical aerodynamics accounts for $11.535 million or 14.3%. As indicated by Figure 62, peak funding of $19.5 million occurs in FY 1975.

It should be noted that the expenditure of $80.405 million for the program outlined in this section does not represent the total expenditure required for commitment to a go-ahead on a commercial transport program. The R&D tasks and additional development normally borne by the industry, including the development of advanced engines, are not included in the cost summary.

TABLE IX. TOTAL PROGRAM COSTS IN MILLIONS OF DOLLARS

Technical category	Fiscal year								Total
	1973	1974	1975	1976	1977	1978	1979	1980	
1 Advanced materials	2.825	5.495	9.495	5.120	3.670	2.170	1.470	1.470	31.715
2 Supercritical technology	1.270	1.910	2.695	2.795	1.465	0.800	0.600		11.535
3 Noise reduction	0.865	1.635	1.900	2.100	2.710	2.025	0.025		11.260
4 System studies	0.595	3.360	4.855	6.680	4.000	3.000	2.000		24.490
5 Active controls	0.380	0.185	0.540	0.300					1.405
Totals	5.935	12.585	19.485	16.995	11.845	7.995	4.095	1.470	80.405

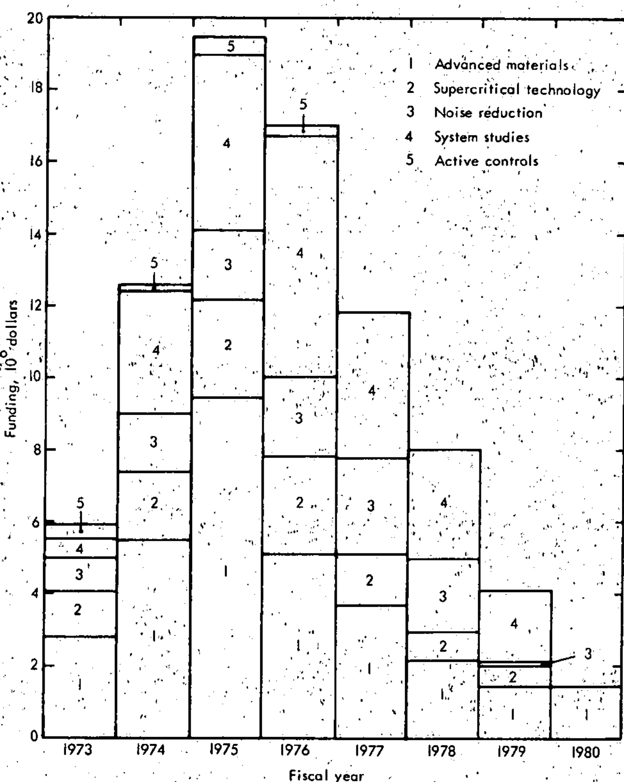

Figure 62. Program cost summary.

10.0 R&D DEVELOPMENTAL EQUIPMENT REQUIREMENTS

10.1 TECHNOLOGY DEMONSTRATION VEHICLES

Because of the large steps toward advanced technology which have been shown to be practicable in Volume I of this report, the characteristics of the final in-service transonic transport airplane will be significantly different from those of any prior airplane. Since analytical computations and ground test facilities have only a limited capability to simulate actual flight conditions, extensive flight experience is the only means to provide precise information on the final operational characteristics of new aircraft. Furthermore, some highly significant considerations which are not design parameters were only brought to light long after new models of aircraft had been in service for appreciable lengths of time. "Jet upsets" due to turbulence and deep-stall problems are typical recent examples. Additionally, information of great importance from operational and economic standpoints is frequently uncovered only as a result of practical operating experience. Maintainability of structures with a high proportion of composites will likely fall in this category.

The requirement for flight demonstrator vehicles therefore extends far beyond "proof-of-concept missions," and, since many of its functions will be exploratory, the benefits from a demonstrator vehicle are difficult to quantify. The items of useful information which can be derived from flight programs are, in many instances, dependent on the size of the vehicles used, since many airplane characteristics depend upon physical phenomena which are controlled by the size of the vehicle, or by inherent relationships between size and weight. Figure 63 shows a highly simplified diagram indicating several fundamental properties of an air vehicle dependent on size and the manner in which they interact to cause effects on the final aircraft operating characteristics. Since many of these fundamental properties are functions of a number of design parameters or flight conditions, (e.g., size, weight, altitude, and speed), the possibility exists that appropriate simulation of certain phenomena can be achieved by properly scaling variables in relation to each other. The following paragraphs present a brief discussion of such possibilities, primarily in relation to aerodynamic characteristics.

10.1.1 Cruise Configuration

Available NASA high-speed tunnels and other facilities permit testing to about $R_N = 10 \times 10^6$, but the projected cruise condition for the M = 0.95 transport is in excess of 50×10^6. The importance of this gap is a matter for speculation. Experience with the present generation of subsonic aircraft has included several examples of the difficulty of making this extrapolation, the C-141 wing-load distribution being one. Semi-empirical techniques have been evolved to account for the changes to shock/boundary-layer interaction phenomena that take place with increasing R_N and the current joint NASA/Lockheed test program on the C-141 will hopefully confirm those techniques. The nature of these phenomena could, however, be significantly different for supercritical airfoils at the higher M under consideration. Without adequate flight validation, this would remain a significant risk area.

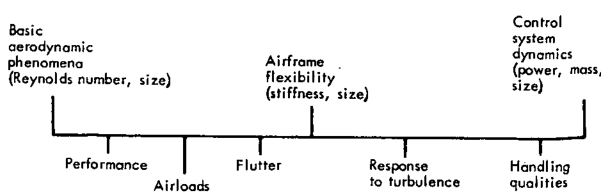

Figure 63. Aerodynamic design considerations.

It is not essential to use a completely full-scale vehicle to attain full scale R_N. Tests with a somewhat smaller vehicle at the same Mach number at lower altitudes can yield the required values. If, however, the need to achieve full scale C_L as well as full scale R_N is also recognized, the wing loading to which the research vehicle must be designed quickly exceeds practical bounds as the size of the vehicle is reduced. Figure 64 illustrates the combinations of test altitude, required wing loading and design cruise speed which will allow tests to be made at the cruise M, R_N and C_L values of the present Lockheed M = 0.95 configuration as functions of research vehicle size. It also shows the limitations for any particular test vehicle in terms of achievable R_N. Consider a JetStar-sized vehicle, with wing area of about 500 ft² (46.5 m²). To attain full-scale R_N = 52.9 X 10^6, tests would have to be carried out virtually at sea level, implying a V_{MO} of 614 KEAS (92.1 m/s). To accomplish full-scale C_L = 0.47, in level flight, the vehicle would need to have a wing loading of 590, which is clearly ridiculous. Conversely, if a reasonable wing loading of 150 is assumed and a very strong flight-test structure allowing a V_{MO} of say 500 KEAS (75 m/s), testing would still be restricted at M = 0.95 to 12 000 ft (3660 m), giving a max R_N = 38 X 10^6 at a C_L of 0.12.

The very stiff structure implied by this high V_{MO} would also make the vehicle unrepresentative from an aeroelastic distortion viewpoint and further limit the validity of the simulation.

The use of a 707/DC8 size of research vehicle, with a wing area of 2800 ft² (260.4 m²) greatly improves the research potential. Testing at 29 000 ft (8845 m), implying a V_{MO} of only 345 KEAS (51.8 m/s) would achieve the desired R_N. A design wing loading of 190 would be required to give the full scale C_L, implying very poor takeoff and landing performance, but operation from a research facility such as Edwards would be feasible.

Overall, it is considered that from the cruise performance veiwpoint, any research vehicle smaller than approximate 707/DC8-size would offer little advantage in bridging the tunnel-to-full-scale R_N gap over that currently being achieved with the SCW F-8.

10.1.2 High Lift Configurations

Scale effect on maximum lift coefficient, and on the trimmed drag versus C_L at takeoff and landing flap setting, both need flight validation to enable the detail design to proceed with

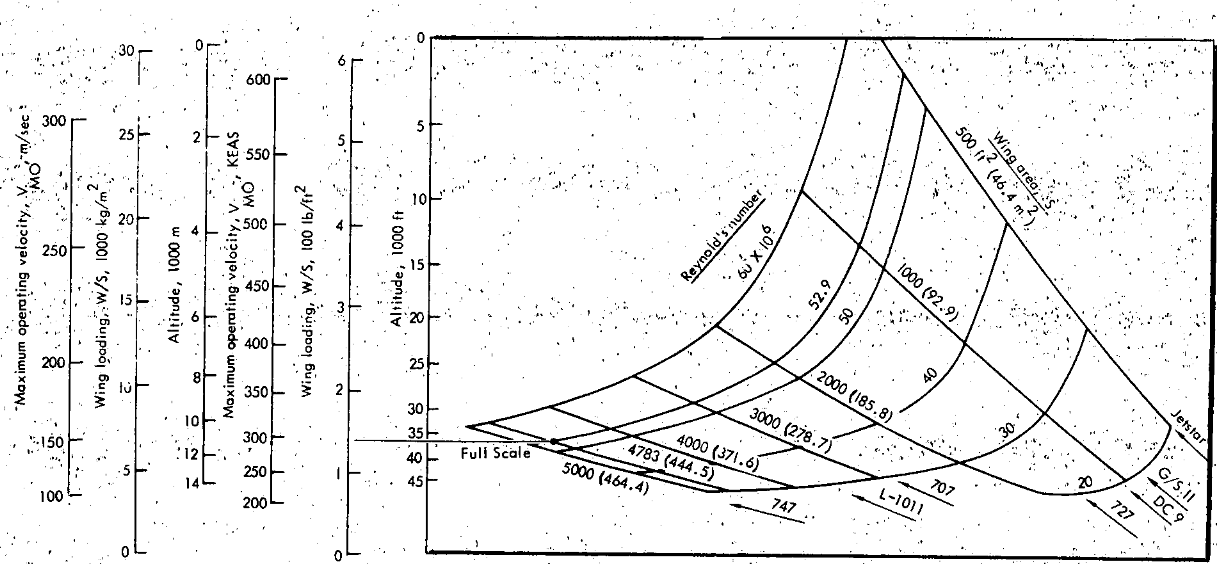

Figure 64. Research vehicle characteristics to demonstrate full scale vehicle performance of M = 0.95, altitude = 37 000 ft (11 300 m), and C_L = 0.47.

confidence. The unusual planform and the very thin, cambered trailing-edge flaps which result from the SC wing section are features for which no high-R_N experience exists. Extrapolation of tunnel data measured at about $R_N = 4 \times 10^6$ could be dangerous, particularly for $C_{L\,MAX}$, since the effect of the large highly-swept inboard leading-edge extension introduces the possibility of detached stable vortex flow over the inboard part of the wing at high lift coefficients. The effect of Mach number on maximum lift is also a matter of concern. To fully establish the Reynolds-number and Mach-number effects, the full-scale combinations of these parameters must be attainable with the research vehicle. An illustration of likely capabilities of different size vehicles is shown on Figure 65. A tentative carpet of $C_{L\,MAX}$ versus M and R_N has been constructed, which is largely for illustrative purposes and does not represent a developed estimate for the M = 0.95 vehicle. It does however, indicate trends based on conventional vehicle experience and is representative of the M = 0.95 configuration at full-scale conditions. The shaded area represents the range of values of $C_{L\,MAX}$ that would be obtained during evaluation of the $C_{L\,MAX}$ levels appropriate to operating at wing loading between 85 and 140 through an airport altitude band from sea level to 10 000 ft (3050 m). The ability of research vehicles, sized at 500-, 2000- and 3000-ft^2 (75, 186, and 279 m^2) wing areas, to validate this full-scale region is indicated by the labeled points. It is clear that a small vehicle would fall short of the interesting region and could give a misleading indication of full-scale characteristics. The points shown at 500 ft^2 (75 m^2) are for 1-g stalls at two wing loadings, 140 and 200, and for sea level and 10 000 ft (3050 m).

The effects of Mach number and R_N could be extended to higher levels by performing accelerated stalls, giving the effect of high wing loading, but it is clear that the region of full-scale interest could never be attained. As size is increased, the gap between research

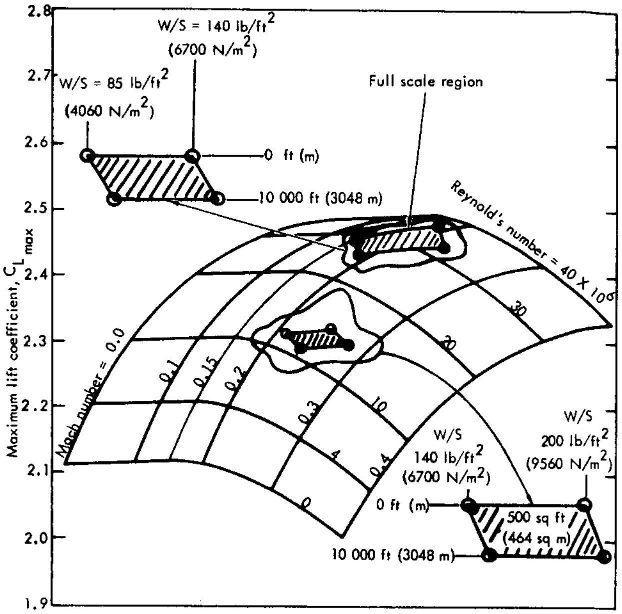

Figure 65. Research vehicle characteristics required to validate low speed full scale $C_{L\,max}$.

vehicle capability and full-scale conditions obviously narrows and it can be seen that a 707-sized vehicle is adequate to give good representation of full-scale conditions.

The simulation of full-scale conditions to establish the low-speed drag characteristics is of less importance than the maximum-lift aspect. Mach number is of less significance and the effect of Reynolds number is likely to be small and predictable. Nevertheless, larger vehicles give better results and the provision of strength

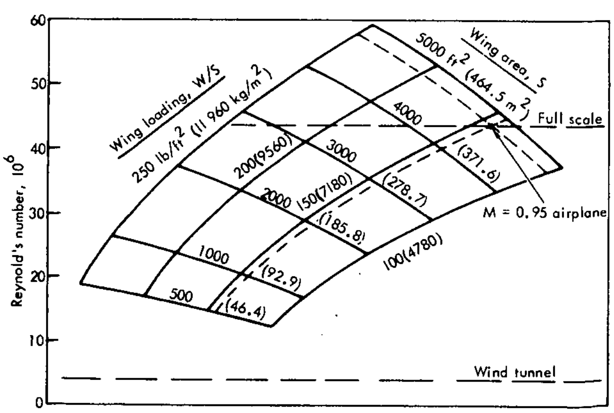

Figure 66. Reynolds number of different size research vehicles for critical low speed drag, C_L = 1.6 at sea level, takeoff flap.

to allow high wing loading, and high flaps-extended speeds minimize any differences. Figure 66 shows the ability of various size research vehicles to attain full-scale R_N. The critical high-lift configuration drag is likely to be the takeoff case at climbout speed V_2. The C_L for this case is about 1.6, and the full-scale R_N for this case is 43.6×10^6. Clearly this cannot be approached, with any realistic design wing loading, by any research vehicle smaller than the 707.

10.1.3 Stability and Control

Vehicle size is not expected to be very significant in establishing static stability and control derivatives, since the effect of Reynolds number is small, at least in the low-C_L regions. Non-linearities in the high-C_L regions are, however, likely to be subject to variation with R_N, the likely trend being an improvement at high R_N. Results obtained on a small research vehicle relating to pitch-up boundaries, speed instability at high M, and possible buffet boundary could well be conservative when applied to full-scale design. A corresponding situation might also result about the lateral and directional axes. A more serious drawback to the use of a small research vehicle is the inherently less-flexible structure that would result, which would degrade the realism of the representation of static and dynamic aeroelastic characteristics. This would be further aggravated if the small vehicle were to be designed to high wing loading and high V_{MO}, as previously suggested from a performance viewpoint, to allow testing at higher R_N and C_L combinations.

While substantial modification of the airplane response to control inputs, and to its own motions, can be achieved by use of artificial stability systems to provide a simulation of flying qualities for an airplane of a different size, use of such techniques in the context considered here would simply obscure the basic phenomena which are the object of the investigation. Other simulation concepts, however, might very well permit studies of these basic phenomena by the use of flight vehicles considerably smaller, and therefore less costly, than the service transport airplane. A comprehensive study of the simulation possibilities available through appropriate handling of the fundamental scaling parameters available, with detailed attention to the interactions among the various simulation requirements, should be conducted to determine the most economical means of obtaining the required information.

10.1.4 Structural Considerations

Scaling the structure to a vehicle smaller than an approximate 250 000 lb (113 000 kg) gross-weight airplane would not give adequate simulation of the structural characteristics of the airplane to produce reliable technical data. The wing structure follows the square-cube law, and scaling down to 1/3 size actually means scaling such parameters as torsional constant, J, and the moment of inertia to 1/9-size. The internal loads in the surface would be scaled to $1/\sqrt{3}$ which would reduce the structural member sizes to approximately $0.58 \times$ the full-scale wing box. Attempting to go below a 1/3 scale would be almost impossible to simulate the structure of the lifting surfaces.

The fuselage structure possible could be scaled down to approximately a 150-in. (3.81 m) diameter at the maximum area-ruled cross section. This would be approximately 1/8 of the full-scale volume and result in skin gages equal to 1/2 of those for the full-scale airplane.

10.2 LARGE GROUND TEST FACILITIES

Previous discussions in this report have indicated the need for aerodynamic data at high Reynolds numbers to improve the simulation of flight characteristics. Recently completed NASA flight testing, using the F-8 SCW research airplane, has demonstrated some of the differences which might appear between wind-tunnel and flight data resulting from scale effects. The need for ground test facilities to permit the acquisition of data at full flight Reynolds numbers has long been recognized. This need has received greater attention in recent years as a result of several instances in which unanticipated Reynolds-number effects have been encountered during airplane development programs. Joint efforts by NASA and DOD are now underway to define the requirements for new facilities and to develop plans for construction. Figure 67, copied from a recent NASA presentation on this subject, emphasizes the importance of obtaining precise data from ground test facilities early in an airplane development program. At this point, program costs are low and any redesign required by such data can be accomplished without major program impacts.

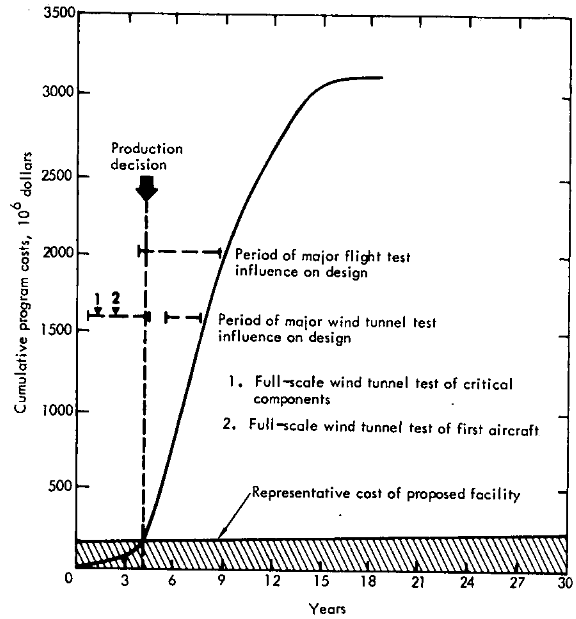

Figure 67. Aircraft funding schedule.

Information developed by the joint NASA-DOD studies has led to conclusions that three specific ground test facilities have sufficient priority to warrant the immediate initiation of planning and preliminary design:

(1) High Reynolds number transonic wind tunnel.

(2) Full-scale subsonic wind tunnel.

(3) Large engine-test facility.

TABLE X. GROUND FACILITY REQUIREMENTS

Facility	Size	Cost, 10^6 dollars	Operational date
High Reynolds number transonic wind tunnel	Test section 8 ft (2.438 m) X 10 ft (3.048 m) to 16 ft (4.871 m) X 20 ft (6.096 m)	37.5	1976
Full scale subsonic wind tunnel	Test section 150 ft (45.72 m) X 200 ft (60.96 m)	200	1980
Large engine test facility (Engines up to 100 000 lb (444 800 N) thrust)	Test cell 28 ft (6.534 m) dia. X 50 ft (15.24 m)	230	1980

It is expected that these would be national facilities, available for developmental testing for both commercial and military aeronautical programs. Planning for these facilties is not yet complete. Table X summarizes some characteristics of the facilities under consideration and provides approximate funding and schedule information.

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